VERLAG DER TECHNISCHEN UNIVERSITÄT GRAZ

Stefan Marschnig

iTAC – innovative Track Access Charges

RR 1

MONOGRAPHIC SERIES TU GRAZ
RAILWAY RESEARCH

Stefan Marschnig

iTAC – innovative Track Access Charges

Monographic Series TU Graz

Railway Research RR

Series Editor:

Univ.-Prof. Dipl.-Ing. Dr.techn. Peter Veit

Monographic Series TU Graz

Railway Research Volume 1

Stefan Marschnig

---

iTAC – Innovative Track Access Charges

This work is based on the habilitation *"iTAC – Innovative Track Access Charges"*, presented at Graz University of Technology, Faculty of Civil Engineering in 2016.

Cover photo	Stefan Marschnig
Cover layout	Verlag der Technischen Universität Graz

www.tugraz-verlag.at

Print
ISBN 978-3-85125-493-8

E-Book
ISBN 978-3-85125-755-7
DOI 10.3217/978-3-85125-493-8

Vorwort zur Schriftreihe Railway Research

Das Institut für Eisenbahnwesen und Verkehrswirtschaft der Technischen Universität Graz beschäftigt sich als Institut der Fakultät für Bauingenieurwissenschaften mit der Eisenbahninfrastruktur, und zwar den bautechnischen Fragen des Errichtens des Fahrwegs und des Betriebs der Strecken und damit eng verknüpft seiner Wartung und Instandsetzung. Damit sind sämtliche erforderlichen Bausteine für eine Betrachtung des gesamten Lebenszyklus der Infrastruktur abgedeckt.

Das Einbeziehen wirtschaftlicher Bewertungen der Lebenszyklen erlaubt den Schwerpunkt „Nachhaltigkeit" umfassend in technischer, betrieblicher und wirtschaftlicher Sicht zu behandeln. Die Forschungsfragen betreffen dabei das Gleislageverhalten mit der Zielsetzung dieses prognostizierbar zu machen und damit die Voraussetzung für präventive Instandhaltung zu schaffen. Die Forschung des Instituts in betrieblicher Hinsicht umfasst die Fahrplangestaltung und eine auf Nachfrageprognosen aufbauende Netzentwicklung sowie Auswirkungen unterschiedlicher Verfügbarkeiten. Alle diese Themen werden im Forschungsbereich Life Cycle Management einer umfassenden wirtschaftlichen Bewertung zugeführt.

Mit diesem Ansatz versucht das Institut für Eisenbahnwesen und Verkehrswirtschaft seinem Anspruch, nämlich das System Eisenbahn in Forschung und Lehre zu vertreten, gerecht zu werden.

Innovative Track Access Charges

Die Liberalisierung des Eisenbahnwesens Europas hat zur organisatorischen Trennung von Bahninfrastruktur und Betrieb geführt. In diesem System bezahlen Eisenbahnbetriebsunternehmen der Infrastruktur Benützungsentgelte. Diese „Schienenmaut" ist der einzig verbleibende Link zwischen den beiden Teilen des Systems Bahn. Die Schnittstelle ist damit der Kontaktpunkt Rad-Schiene. Um eine Systemoptimierung über diese Schnittstelle hinweg zu ermöglichen, ist es erforderlich, die Schienenmaut verursachungsgerecht auszugestalten. Dazu wurden die Wechselwirkungen von Fahrzeug und Fahrweg und zwar spezifisch für die unterschiedlichen Fahrzeuge und die unterschiedlichen Fahrwegsituationen erforscht und in einen Zusammenhang mit dem daraus resultierenden spezifischen Instandhaltungs- und Re-Investitionsbedarf gesetzt. Die damit verknüpfte Wirtschaftlichkeitsrechnung erlaubt auf Basis der Lebenszykluskosten verursachungsgerechte Trassenpreise zu berechnen. Da diese Forschungsarbeit ein „High-End-Produkt" im Bereich der technisch-wirtschaftlichen Nachhaltigkeit des Systems Bahn darstellt, freut es mich ganz besonders, Ihnen damit die Schriftenreihe „Railway Research" vorstellen zu können.

Peter Veit

Preface

This paper covers work and research I have done in the past ten years, but also combines my own work with others' knowledge. A remarkable part of the data and results used in the evaluations for iTACs was originally meant for other purposes. From an engineering point of view, the interest in track access charging started in 2003 with evaluations for ÖBB's traction unit factor (Triebfahrzeugfaktor), motivated by the fact that vehicle quality either decreased or did not improve. Track access charging is an interface topic, bringing together engineering, economic, and juridical aspects. It is a long process to match very different points of view. In numerous discussions, I had the chance to learn a fair amount by listening to points of view from other disciplines. I am grateful for this experience, even though it is sometimes difficult to discuss topics when speaking different idioms. While there are numerous economic approaches, this work is intended to provide an engineering point of view.

This is the moment to highlight the importance of support. My grateful acknowledgements are due to my mentor Peter Veit. In addition to all the knowledge and skills I was able to learn at his side, his unlimited faith in my research and the great support he provided wherever and whenever it was needed is outstanding. Following his ambition to transfer engineering knowledge to the cross-disciplinary unit of the euro helps a great deal in interdisciplinary discussions. I would also like to emphasise the importance of my former professor, Klaus Riessberger, who never ceased to point out that railway engineering is system engineering, and who encouraged me to think outside the (civil engineering) box.

From the large number of colleagues to be acknowledged with deep thanks, I would especially like to thank three important people who accompanied me on my way to the kind of charges presented in the paper: Dieter Jussel gave me his full attention whenever vehicle properties were subject to confusion. His input was important throughout my work. When there were cost accounting issues, Marko Koren (ÖBB) was always by my side to discuss variability of depreciation and other topics. I was able to discuss all the aspects of vehicle-based charging with Ingolf Nerlich (SBB) at any time, day or night. Thank you, everyone!

I can hardly express my enormous gratitude to Jochen Holzfeind (SBB). His broad and integrated understanding of track asset management gave me the possibility to contribute to the Swiss wear factor (Verschleissfaktor). Being able to contribute significantly to both the wear formula itself and the cost calibration provided me with two outstanding steps in my career: the unusual opportunity to transfer research knowledge into real life and the possibility of being involved in a topic from the very beginning to the implementation.

I would like to express my sincerest gratitude to the CEOs Andreas Matthä and Siegfried Stumpf at the Austrian Federal Railways (ÖBB). By giving me the possibility to calculate the demand-based approach for the Austrian network, they supported me and enabled a major step forward to be taken in research. At this point, I would also like to thank all the ÖBB colleagues, particularly those from the track department.

I would like to thank my colleagues at the university, Markus Enzi, Matthias Landgraf, Fabian Hansmann, Anna Frisee, Stefan Walter, Armin Berghold, and Georg Neuper, for all their help and support. The university is a great place to work, thanks to them. I also wish to thank my colleagues from KTH, namely Evert Andersson and Johan Öberg, for the long, productive, and controversial discussions. This inter-universal collaboration is often lacking.

Finally, I humbly thank my family, Katharina, Noah, and Levi. They had to spend too many hours without me when I was working on and writing this paper and carrying out the research and projects linked to it, instead of being at home, where I should have been.

Abstract

Liberalisation of the railway system and therefore separation of infrastructure managers and railway undertakings are the European Commission's policy to increase the popularity of the transport mode again. Expected effects have not yet materialised. The multiple organisational interfaces do not support system optimisation, rather the opposite. Track access charges are the remaining link between infrastructure and vehicles, the most crucial technical interface of railways. Of course, in-efficiencies contribute to higher overall costs, but system costs are influenced most at engineering's level.

The legal framework for the charges changed several times since the early 1990ies. The recast Directive 2012/34 and the accompanying Regulation 2015/909 clarified open points successfully. In general, levying charges must be based on the cost that is directly incurred by operating a train service. From an economic point of view, this can be translated to the marginal cost principle. The engineering aspect of extracting the costs due to a single train run is a challenging task. Considering the rail-wheel-interaction, the result changes due to infrastructure design, operational boundary conditions, and vehicle properties. The cost-by-cause principle needs a detailed analysis of the technical interaction.

In mixed-traffic networks, another question arises: who pays for what? Different train services demand for different infrastructure assets and different quality levels. It is necessary to consider these differences in order to assure fair charges for all users.

Innovative track access charges should be based on four principles:

Principle I: Marginal Cost-based Charging
The costs of high-loaded tracks show the level of wear and tear costs. In the case of higher costs on low-loaded lines, residual costs will occur, which are defined as costs that are part of "providing the infrastructure". This definition prevents costs being shifted from low-loaded lines to higher loaded ones.

Principle II: Line or Line Segment based Charging
The differences between the wear and tear costs of different line characteristics are much too high to be averaged. Line-based charges are necessary in order not to shift costs from high-cost lines to low-cost lines.

Principle III: Wear-based Charging

Wear-based means vehicle-based, of course. There is no way to approximate the wear costs of track without using a track deterioration model that consists of vehicle properties as well as infrastructure and operational properties (speed). The increased complexity is justified by much better model accuracy.

Principle IV: Demand-based Charging

The specific demand of a train service leads to assets of a certain amount and quality. If the demand is obvious, different charges are already standard (e.g. charges for station use). In mixed-traffic networks, track quality demand and turnout demand differ for different market segments. If this is not taken into consideration in the charging scheme, some trains pay for costs incurred by other trains. This is cross-financing and not in line with the targets of the European Union directives.

This paper deals with all these principles aiming for a charging scheme based on the best available understanding of cost causation that is still suitable for implementation.

Kurzfassung

Die Strategie der Europäischen Kommission zur Wiederherstellung der Popularität des Verkehrmodus‘ Schiene ist die Liberalisierung des Sektors und damit die Trennung von Infrastruktur und Eisenbahntransportunternehmen. Die erwarteten Effekte sind bisher ausgeblieben. Die unzähligen Schnittstellen hingegen wirken der Systemoptimierung eher entgegen. Die Trassenbenützungsgebühren sind der verbleibende Link zwischen Infrastruktur und Fahrzeugen, der sensibelsten technischen Schnittstelle der Eisenbahn. Abgesehen von Ineffizienzen, die höhere Gesamtkosten nach sich ziehen, werden die Systemkosten maßgeblich auf Ingenieurslevel festgelegt.

Die gesetzlichen Grundlagen für die Festsetzung der Trassengebühren änderten sich mehrmals seit den frühen 1990-er Jahren. Die Richtlinie 2012/34 und die begleitende Umsetzungsverordnung 2015/909 konnten die fraglichen, offenen Punkte klären. Grundsätzlich sind die Entgelte auf Basis jener Kosten festzusetzen, die unmittelbar aufgrund des Zugbetriebs anfallen. Kostentechnisch ist dies gleichbedeutend mit den variablen Kosten einer Zugfahrt. Technisch ist die Darstellung der Infrastrukturkosten einer einzelnen Zugfahrt eine Herausforderung. Berücksichtigt man den Rad-Schiene-Kontakt, so muss sich das Ergebnis je nach Infrastrukturdesign, betrieblichen Randbedingungen und Fahrzeugeigenschaften ändern. Die Umsetzung des Verursacherprinzips bedarf daher einer detaillierten Betrachtung der technischen Wechselwirkungen.

In Mischverkehrsnetzen stellt sich zudem die Frage, wer wofür zahlen soll. Unterschiedliche Zugfahrten bedürfen unterschiedlicher Infrastruktur und unterschiedliche Qualitätszustände. Um eine faire Bepreisung für alle Nutzer sicherzustellen, müssen diese Unterschiede Berücksichtigung finden.

Innovative Trassenbenützungsgebühren sollten daher vier Prinzipien genügen:

Prinzip I: Entgelte auf Basis variabler Kosten
Auf hoch belasteten Gleisen lassen sich die verschleißabhängigen Kosten zeigen. Auf schwächer belasteten Abschnitten zeigen sich auch in der Instandsetzung höhere Kosten, die Teil der Kosten für die Bereitstellung der Infrastruktur“ sind. Diese Definition variabler Kosten auf hochbelasteten Strecken verhindert die Umlagerung von schwach auf hoch belastete Strecken.

Prinzip II: Strecken- oder streckenabschnittsbezogene Entgelte
Die Unterschiede der verschleißgetriebenen Kosten für unterschiedliche Streckencharakteristika sind deutlich zu hoch, um gemittelt zu werden. Streckenbezogene Entgelte sind notwendig um Kostenumlagerungen von teuren auf günstigere Strecken zu verhindern.

Prinzip III: Fahrzeugbasierte Entgelte
Verschleißbasiert bedeutet notwendigerweise fahrzeugbasiert. Es ist unmöglich Verschleißkosten darzustellen, ohne ein Verfallsmodell für die Infrastruktur zu verwenden, das Fahrzeugeigenschaften ebenso berücksichtigt wie die Infrastrukturrandbedingungen und die Zuggeschwindigkeit. Die höhere Komplexität solcher Ansätze lässt sich mit einer deutlich verbesserten Modellgenauigkeit rechtfertigen.

Prinzip IV: Bedarfsbasierte Entgelte
Jedes Marktsegment führt zu spezifischen Anforderungen an die Infrastruktur in Bezug auf Anlagenmenge, -ausgestaltung und -qualität. Ist dieser Bedarf offensichtlich, sind eigene Entgeltkomponenten bereits als Standardlösungen verankert (z.B. Entgelte für die Nutzung von Verkehrsstationen). In Mischverkehrsnetzen sind die unterschiedlichen, spezifischen Anforderungen der Marktsegmente hinsichtlich Gleisqualität und Weichenmenge schwer zu differenzieren. Werden sie Unterschiede bei den Entgelten jedoch nicht berücksichtig, kommt es zu Verlagerungen von Kosten von einem Marktsegment hin zu anderen. Eine solche Quersubventionierung ist jedenfalls nicht Ziel der Richtlinien der Europäischen Union.

Die vorliegende Arbeit behandelt diese Prinzipien mit dem Ziel, ein Preissystem zu entwerfen, das einerseits dem besten Verständnis über die Kostenverursachung entspricht, andererseits aber auch umsetzbar ist.

Content

1

Separation – a New Railway Era

1.1 A Brief Historical Overview – the Rise and Fall of the Railways

Railways are the oldest mode of transport in non-urban traffic today and have a long and eventful history. In the early days of the railways as we know them today, in the first half of the 19th century, railways were a revolutionary development in the mobility sector. In passenger traffic, up to 50 km/h could be reached – incredible for that time. Combined with unprecedented comfort for travellers, this led to a rapid rise of the railways. In freight transport, the limits of transport loads and distances disappeared almost overnight. All this, despite the still – at least compared to today's standards – modest technological opportunities. This happened at a poor level of technology compared to today's standards. These the early days, the golden years of railways, were more than 150 years ago, but still have a massive impact on the system – especially on the infrastructure.

The early railway days are strongly associated with a great entrepreneurial spirit. Both the construction of railway lines and running the trains had been in private hands. Public authorities only awarded concessions for new lines. Europe was covered, line by line, at what was a fascinating speed from today's perspective. Today's lead, planning, and construction times resulting from legal requirements and in-depth considerations concerning environmental and social consequences often reach 15 years or even far more. Between 1840 and 1880, 350,000 kilometres of railway lines had been built worldwide, and in the three years until 1883, 100,000 more. The construction of the 2,800 kilometre-long US Transcontinental Railroad took only four years.

A military aspect was soon added to the entrepreneurial spirit: The possibility of moving military equipment and troops easily and quickly led to increasing state activity in the railway sector. Moreover, public authorities had to replace private investors for branch lines. Public influence grew when the first railway undertakings went bankrupt. To varying degrees, the two main reasons appeared to be:

- The immense investments of the infrastructure assets were only able to be re-financed – if at all – in horrendous time spans. This weak economic position was accompanied by growing competition between railway undertakings with parallel lines.
- Financial reserves for the high investment costs of railway infrastructure were replaced in some countries by an increasing desire to convert the lucrative freight lines into state property.

Finally, yet significantly, the waning star of political liberalism and the rising star of nationalism led to an ever-expanding state railway sector. The Franco-German War of 1870 and the First World War demonstrated the tremendous power of the railway, which resulted in differing time frames, but ultimately to state railways throughout Europe.
While the whole sector was being reorganised, it also began to decline: Back in the 19th century, railways had contributed to industrialisation and a strong industry sector itself. At the beginning of the 20th century, railways gradually fell victim to an emerging traffic mode in both freight and passenger traffic: The age of the automobile was heralded. The steadily improving technology in the automotive sector since the beginning of the century and not least the destructive power of the Second World War put pressure on the railways. During the years of reconstruction, the entire railway infrastructure, tracks, bridges, stations, and shunting yards – heavily under fire due to their strategic importance – had to be rebuilt at enormous financial expense. Locomotives and wagons were in short supply. This reconstruction was superimposed by another technological change: The electrification of the railways had begun. Nevertheless, the mass motorisation that began in the mid-1950s led to a rapid decline of the railways' modal split share. The importance of the railways declined further, which was increasingly due to the developing air traffic. For Germany, the decline of rail freight is well documented: While the modal split share in 1950 was still at about 55%, it fell to only around 35% in mid-1960 – to the same level of road freight transport. While the latter rose to around 70% today, rail freight slumped to well below 20%.

At the end of the millennium, the situation of the railways was devastating from a European perspective: The market share in the modal split amounted to just 8% in freight, and the passenger share was even lower at 6%. [1] International comparisons, such as with the USA (40% market share of the freight), suggested that the decline of the railways in Europe was not inevitable. At a European level, transport policy has been looking for solutions that would ultimately lead to a new era in the railway sector.

Résumé:

- For both passengers and freight, railway transport had been largely replaced by other modes of transport. The already low modal split shares also had negative forecasts.
- Increasing capacity bottlenecks on the road infrastructure and the emerging environmental awareness forced policymakers to see railways as a space-saving and resource-saving option for the transport volumes of the future.
- The state railways seemed de facto unchangeable. Inefficiency, bureaucracy, officialdom, the trade unions’ force, and political influence seemed to be too strong to overcome. The large, ponderous state enterprises were not trusted to be able to accept the battle for market share. Monopoly, rigid structures, a lack of focus on customer needs and non-competitive, technical and operational constraints (especially in cross-border freight traffic) were seen as the main indicators of the railways’ poor performance.

1.2 The European Railway Policy – from the early 1990s to 2015

Having analysed the situation, the European Union set up a plan to revitalise the European railway sector. The goal was to establish a competitive market to break up system-immanent constraints in a first step, and to recover modal split percentages in a second one. Without reverting to the inefficient structures of several competitive integrated railways (in charge of infrastructure and train operation) that were already abandoned in the 19th century, and to additionally release the transport mode from its high financial burden (infrastructure), a new approach had been found: Deregulation, liberalisation, and partial privatisation of the railway sector. The first step was taken in 1991 with the Council Directive on the development of the Community's railways (EEC 91/440 [2]).

1.2.1 Development of the Community's railways (EEC 91/440) – Deregulation

The first directive defined several goals, establishing a new system in a systematic approach:

- The Member States must guarantee that railway undertakings have "*a status of independent operators behaving in a commercial manner and adapting to market needs*".
- A distinction between provision of transport service and operation of the infrastructure should guarantee future development and efficient transport services. For that purpose, these two tasks have to be managed and accounted separately.
- Member States have to take general responsibility for the provision of an adequate infrastructure.
- Member States shall establish rules for setting charges regarding the use of the infrastructure, based on the principle of non-discrimination of any railway undertaking.

This process introduced two principally new bodies, defined by the Directive as follows:

Railway Undertaking (RU): *"any private or public undertaking whose main business is to provide rail transport services for goods and/or passengers with a requirement that the undertaking should ensure traction"*

Infrastructure Manager (IM): *"any public body or undertaking responsible in particular for establishing and maintaining railway infrastructure, as well as for operating the control and safety systems"*

Additionally, it has been foreseen that at least two RUs could establish an association in order to provide transport services between member states (MS). In particular, the RUs have to be independent from any State's influence in establishing their businesses. This applies for decisions concerning association with other RUs, internal organisation, setting of prices for their services, staff and asset policy, and generally their business purpose.

State subsidies to either transport services or infrastructure are to be kept strictly separate, in order to avoid any cross-financing. MS have to assure a sound financial basis for the RUs, and debts could also be accounted separately.

All RUs (and international groupings) have to have access to the infrastructure *"on equitable conditions"*. The user fee for the infrastructure *"may in particular take into account the mileage, the composition of the train and any specific requirements in terms of such factors as speed, axle load and the degree or period of utilization of the infrastructure."* This topic has been considered in more detail in Council Directive 95/19/EC [3]. (Note: charges are analysed separately in this paper in chapter 2.)

The Directive had to be implemented in national law by no later than 1 January 1993.

<u>Résumé</u>:

The Directive foresees a completely new structure of the European railway sector: a state-owned infrastructure, managed by an infrastructure entity (IM), offered to independent railway undertakings to transport passengers and goods. Although new for the railway sector, the principle is well known from other infrastructure. The RUs' situation is fairly well described, whereas the IM's is not. The latter could be a separate entity, state-owned, or even part of one RU. This vague definition led to various different organisational schemes throughout Europe, and, viewed retrospectively, was unable to guarantee non-discriminatory access to the infrastructure, and was therefore changed ten years later in the so-called first railway package.

1.2.2 First Railway Package – Liberalisation Step One

Ten years after the first step, three directives formed the next one: Directives 12/2001 [4], 13/2001 [5], and 14/2001 [6], later known as the first railway package, further deepened the new systems of open access, and fair, non-discriminatory railway traffic with independently managed infrastructure.

In a very brief summary of the most important changes:

- The infrastructure manager should be established as a self-responsible entity concerning management, administration, and internal control.
- Passenger and freight business must be separated, at least in accounting, in order to hinder cross-subsidies between those businesses. This is a consequence of the liberalisation of the freight transport, defined by the fact that RUs are allowed to operate freight services in different Member States without the need to set up international groupings (according to the definitions in Directive 91/440 [2]).
- The open-access policy is widened to terminals and ports with track access.
- The functions licensing of railway undertakings, train path allocation, and track access charging are to be entrusted to bodies independent of any train service provision. In this case the IM is the collector of the charges, but not the charging body.
- An independent regulatory body is responsible for guaranteeing fair and non-discriminatory access to the infrastructure.
- Track access charges for the minimum access package and service facilities *"shall be set at the cost that is directly incurred as a result of operating the train service"* (note: charges are treated in detail in chapter 1.5 of this paper).

<u>Résumé</u>:

These changes are direct consequences of the experience gathered over ten years in the deregulated railway sector. New railway (freight) traffic had not really been established as the incumbents (the former state railways) either hindered new entrances by discriminatory actions in train path allocation or track access charging or in using state subsidies granted for passenger services for aggressive price policies in freight operation.

The sector became much more complex due to the additional topics to be covered but, on the other hand, only these changes provide room for the goals already defined ten years before.

1.2.3 Second, Third, and Fourth Railway Package – Liberalisation Step 2 and 3

Within the time period from 2001 to 2015, several directives had been published, setting legislative rules for businesses in the railway sector. Train driver licences, passenger rights, and safety issues had been topics, as well as much more technical tasks summarised under the buzzword "interoperability". International passenger traffic has already been liberalised, and national passenger traffic will be in the near future. A new European organisation was established in 2004 (second railway package) – the European Railway Agency – in charge of safety, interoperability, and the trans-European railway network (TEN-T).

Meanwhile, the first railway package has been consolidated in the recast (Directive 2012/34/EU [7] establishing a single European railway area). One major change concerns the regulatory bodies, which now have extensive control functions in the field of track access charging.

1.2.4 Summary

The European policy established a structure for the railway sector by separating infrastructure and transport service, which is new for the sector, but very similar to the structure of the transport modes road and air: Competitive transport service providers are offering their services on an open-access infrastructure. The numerous organisational interfaces that had been created by this process are superposed by topics that are still insufficiently solved or even unsolved. Establishing a single European railway area is a challenging task, since the system is very complex and has countless technical and operational interfaces. The organisational interfaces are summarised in the following chapter.

1.3 Organisational Interfaces

The main functions of the system covered by the directive described above are:

- providing train services;
- managing and maintaining the infrastructure;
- allocating the capacity;
- charging the fee for the infrastructure use, and
- the licensing of train service providers.

The following additional functions have to be organised and defined:

- providing the infrastructure;
- regulating the system;
- awarding public service contracts;
- maintaining the rolling stock, and
- investigating accidents.

All these functions have to be covered by entities. Organisational interfaces can be kept fairly low if the infrastructure manager is an independent business unit that is not involved in providing train services. In this case, one solution could be as described in Figure 1.

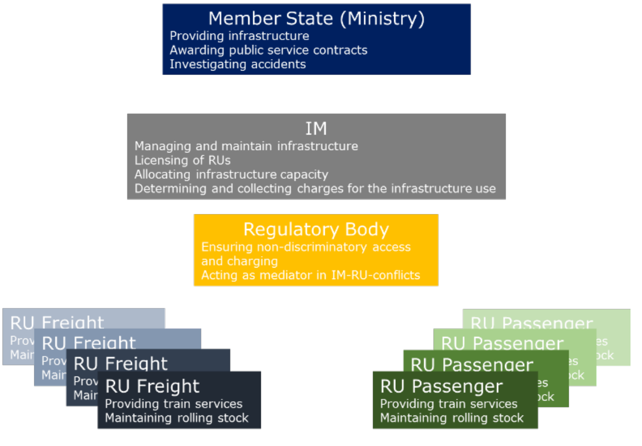

Figure 1 Railway Sector with Independent IM

The main interfaces occur between IM and RUs, and concern train path allocation and track access charges. The first interface is strongly linked with timetabling, the second – if it comes to wear and tear costs (direct costs) – with the rail-wheel contact. Both interfaces have a strong influence on the costs, namely the economics of the single entities and the overall system.

This becomes far more complex if the IM is linked with any train service activity.

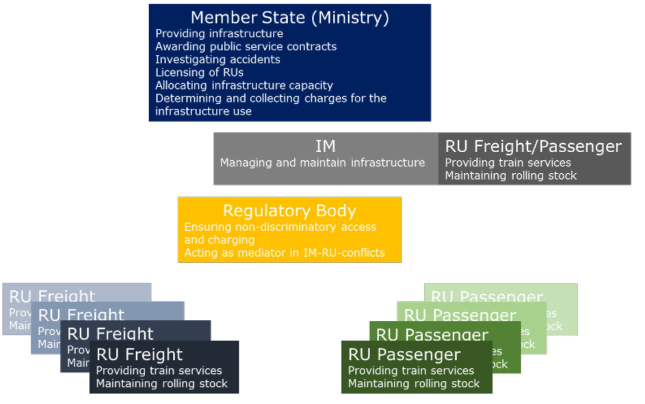

Figure 2 Railway Sector with Non-independent IM

In this case, the essential functions of infrastructure capacity allocation (*"decision-making on train path allocation, including both the definition and the assessment of availability and the allocation of individual train paths"* [7]) and track access charging *("decision-making on infrastructure charging, including determination and collection of the charges"* [7]) must be organised in another entity. This could be any organisation within the ministry. The licensing of RUs can also be shifted to the state authority (ministry).

What does not appear to be a major change leads to further organisational interfaces between the state authority and IM: All three functions require a high degree of knowledge, which must be assured within the ministry, on the one hand, and provided by the IM on the other. Determining charges without access to the cost accounting data is impossible; train path allocation needs detailed infrastructure data. In any case, this works, as some Member States are demonstrating, and the structure is still relatively lean.

Still, this is an idealised situation, far removed from what has happened since the first directive in 1991. The structure depicted in Figure 3 is quite common.

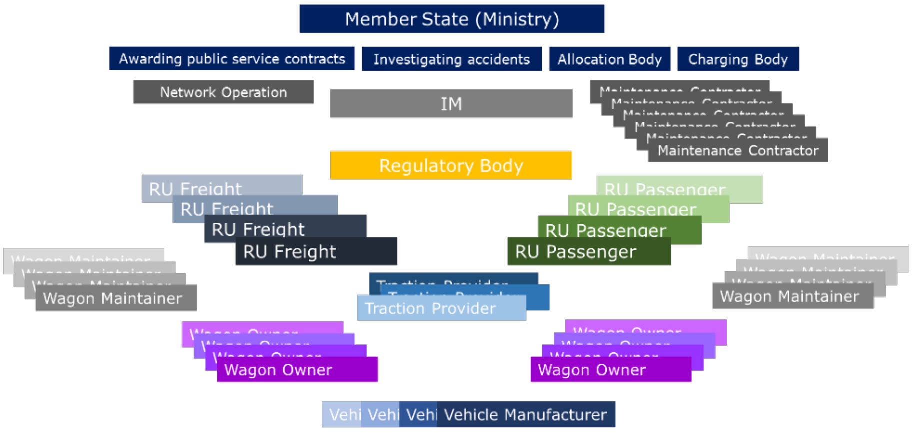

Figure 3 Railway Sector totally deregulated

An infrastructure manager could simply be a legal entity, totally outsourcing maintenance and infrastructure operation. Railway undertakings can offer train services without owning locomotives or wagons. These structures are not theoretically possible, but exist throughout Europe. Privatisation and extreme fragmentation of the IM's responsibilities might be counterproductive and ultimately very costly. After the system collapse in the UK, Network Rail started to bring back maintenance in-house and to compensate for maintenance and renewal backlog. [8]

1.4 Consequences of the Separation/Liberalisation

It is difficult to determine whether the ongoing process of liberalisation is strengthening the railway sector in the intermodal competition. It is almost impossible to determine whether liberalisation helped at all or worsened the situation. The following chapters assess some aspects of the established system. Seven railway-affine countries are singled out and analysed in more detail whenever possible or necessary.

1.4.1 Assessing the Degree of Liberalisation

The process described in chapter 1.2 was implemented in the European Member States to different degrees and with strongly diverging timescales. In monitoring the change of former state railways, the focus was set on splitting the former state railways far more than on the consequences of the process. The Rail Liberalisation Index (LIB) [9][10][11][12] showed the implementation status by country, with two main indicators since 2004: The LEX Index and the ACCESS Index. The single indicators and their weighting are shown in Table 1.

LEX (20% of overall index) (25% in 2002, 30% in 2004, 20% in 2007)		
Organizational Structure	25	
Incumbents' independent status with respect to the state		5
Degree of vertical separation - network/operations		80
Degree of horizontal separation - freight/passenger transport		15
Regulation of Market Access	45	
Market access regime for foreign RUs		40
Market access regime for domestic RUs		40
Legal controlled access to operational facilities		20
Regulatory Authority Powers	30	
General aspects of the regulatory authority		30
Scope of regulation		30
Powers of the regulatory authority		40
ACCESS (80% of overall index) (50% in 2002, 70% in 2004, 80% in 2007)		
Information barriers	5	
Duration for obtaining information		40
Quality of non-personal information provided		30
Quality of personal information provided		30
Administrative barriers	20	
Licence		35
Safety certificate		25
Homologation of rolling stock		40
Operational Barriers	45	
Track access conditions		25
Infrastructure charging system		50
Other service facilities		25
Share of domestic market accessible 2009	25	
Method of awarding transport contracts		20
Compliance with transparency provisions		10
Percentage of the accessible market for RUs		70
Sales services in passenger transport	5	
Rental of space ticket sales offices		50
Access to sales services		50

Table 1 Structure of the Liberalisation Index [12]

With four principle levels predefined (>800 points: advanced, 600-800 points: on schedule, 300-600 points: delayed, and <300 points: pending departure), it can be stated that the process is on schedule (EC average: 706 points). However, there are still large gaps between countries like Spain or France and Sweden or Germany.

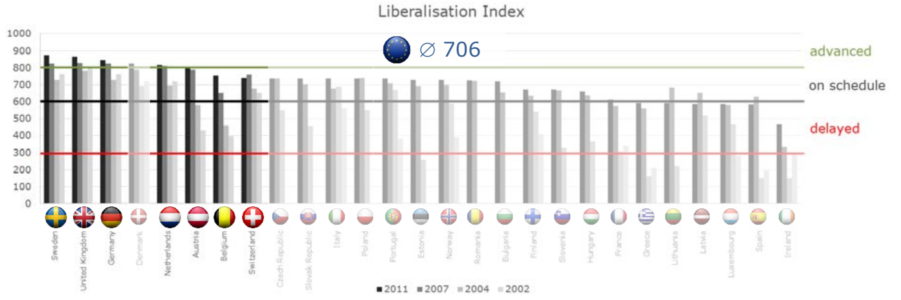

Figure 4 Liberalisation Index

In 2002, the index consisted of one more indicator, the COM Index. As this index describes the consequence of the liberalisation (ex-post evaluation), it was evaluated, but not included in the following years. The values are given in Figure 1. It must be mentioned that the Member States' average is 429 points (without the UK value, only 410). The *"competitive dynamics"* [X] are therefore far behind expectations.

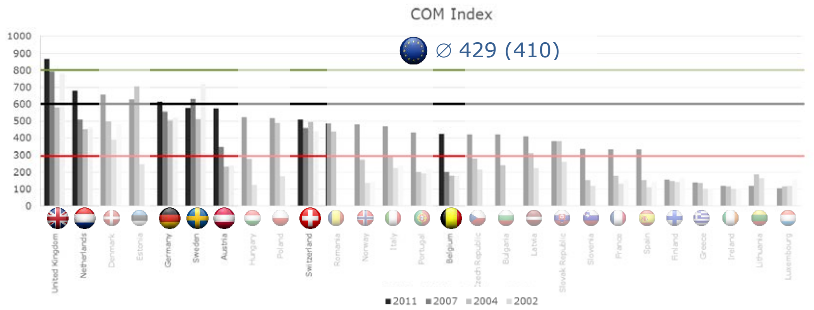

Figure 5 COM Index

Since this analysis shows a completely different ranking for some countries (Estonia, Hungary) and an enormous gap between the UK and the rest of the EU, a detailed view on its input data is wise (Table 2).

COM (not included in overall index) (25% in 2002, not included in 2004, 2007 and 2011)		
Modal split changes	20	
Change in the modal split for rail freight transport (2001 - 2008)		40
Change in the modal split for rail passenger transport (2001 - 2008)		40
Share of modal split for rail freight transport 2008		10
Share of modal split for rail passenger transport 2008		10
Number of external RUs 2009	20	
Certified RUs (excl. incumbent) in relation to network length		40
Ratio of active RUs to certified RUs		50
Number of active RUs providing passenger services on a regular basis		10
Market share external RUs 2009	60	
Market share ext. RUs in terms of transport performance in %		75
Increase in market share of ext. RUs between 2006 and 2009 in %		25

Table 2 Structure of the COM Index [12]

It becomes clear that the performance of the railways is not indicated (the share of modal split is only quoted with a very low number of points), but rather the change over the years. This means, of course, that Member States with a comparably low level in 2001 are quoted higher. In addition, the incumbent’s role (importance of the former state railway) is compared with the new entrance RUs (external RUs). Countries with a high share of external RUs are quoted highly. In the UK, an incumbent is not defined, as the system was already separated into RUs and IMs previously. This results in the high number of points. Estonia has a very high share of transit freight trains, and Hungary sold the freight part of the former state railway to the Austrian freight incumbent. These and many more details are lost in the top-down view.

The evaluation is not able to indicate whether the performance of the railway sector increases. It simply evaluates how the liberalisation proceeds, independent of the possible benefits of this process.

1.4.2 Assessing the Performance

The Boston Consulting Group (BCG) created a Railway Performance Index (RPI) back in 2012 [13]and updated it in 2015 [14]. The performance of Europe's railway sector was described by country, by assessing three main aspects: the intensity of the network use, the quality of service, and safety. The impacts of the single indicators are depicted in Figure 6. For the benchmark, the country with the highest value obtained 10 points, while the one with the lowest was set to 0 points.

Figure 6 Railway Performance Index [13]

BCG stated that with the given methodology, passenger traffic is over-quoted, as punctuality of passenger trains defines around 17% of the total performance. Moreover, a large country tends to result in a higher RPI, as the percentage of high-speed rail only occurs in some (larger) countries. Without looking into and discussing the details, this index is definitely far more appropriate to assess the system's performance than the COM Index described above. In any case, some astonishing simplifications are not even commented on: What about correlations between intensity of use and quality of service? It should be much easier to operate trains punctually if the number of trains in the network were low. A serious inconsistency lies in the description of service quality. If trains run punctually (high score), it would be economically justifiable to levy high fares (low scores), and vice versa. The average fare is therefore much more a consequence of the quality of service than an indicator for it. In combination with the number of high-speed services, which is in itself not good service quality but perhaps a precondition for it, this global indicator is difficult to interpret, or rather, is interpreted arbitrarily.

As values and ranking did not change much from 2012 to 2015, only the latter values are discussed further on. The 2015 ranking does not reveal much new information about the railway mode in the different countries: Switzerland's performance is high, while Bulgaria's is not (Figure 7). All the countries in the first tier show acceptable quality levels, and have intensively used networks and no problems with safety.

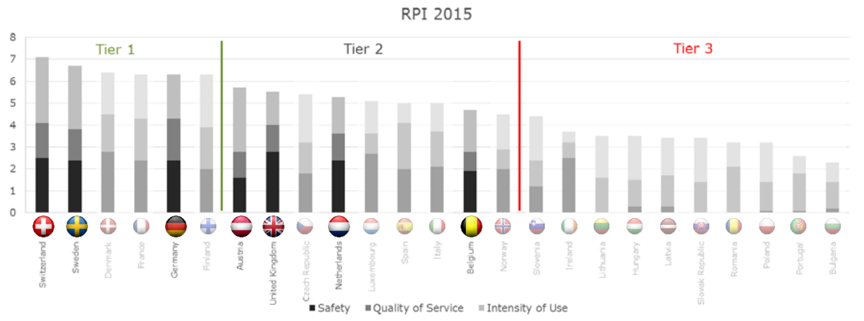

Figure 7 RPI 2015 Ranking

The second tier starts with Austria – obviously with a low safety rating compared to other tier 1 and tier 2 countries (see also the report Railway Safety Performance in the European Union[15]) and a low rate in the Quality of Service indicator, followed by the UK with a low intensity of network use due to a low modal freight share.

The Boston Consulting Group determined whether performance and the degree of liberalisation correlate: Figure 7 shows that there is obviously no dependency between these two aspects. France and Finland, in particular, show low LIB indices, and are hardly in the "on schedule" section, but Switzerland also reaches a maximum. The only comment that can be made is that the advanced liberalised countries are good performers. For the seven countries analysed in more detail, there is no correlation at all (due to Switzerland's high RPI rating).

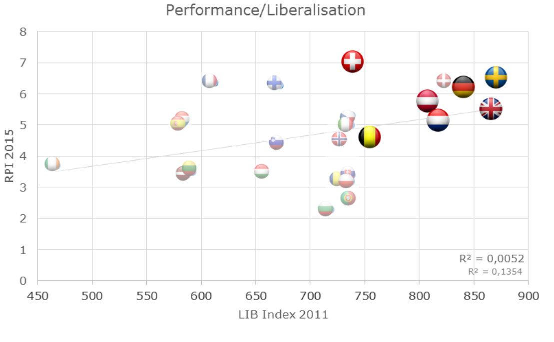

Figure 8 Performance and Liberalisation (according to BCG [14])

The type of governance of the former state railways does not influence the system performance either (Figure 9). The report mentions: *"No correlation between performance and governance: good performers can be found in all four models."*

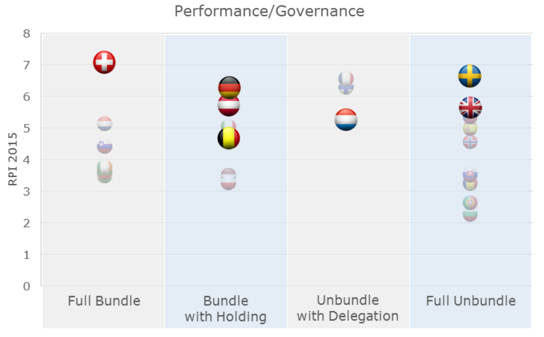

Figure 9 Performance and Governance (according to BCG [14])

Even weaker than the correlation between the degree of liberalisation (LIB Index) and performance is the connection between the RPI and the COM Index [12] (Figure 10). System performance has nothing to do with the fact that more or fewer new RUs are competing on the railway transport market. An efficiently working integrated railway like the SBB in Switzerland can offer high-performing railway transport – and this is true for a market with many different RUs on a completely independent infrastructure like in Sweden. For the seven countries chosen, the correlation is even slightly negative.

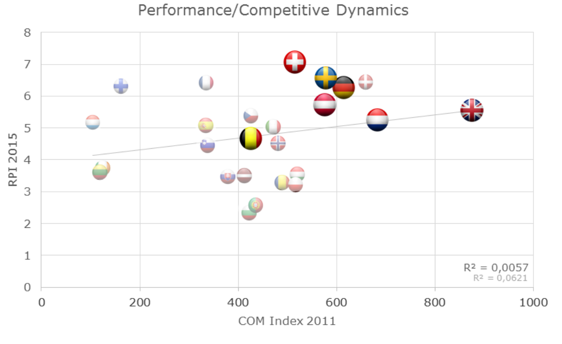

Figure 10 Performance and COM Index

In 2012, the main outcome of the study was that performance correlates with the amount of public subsidies per inhabitant (see Figure 11), consisting of investments (on a six-year basis), infrastructure subsidies for maintenance and operation, and compensation for public service obligations/ordered traffic. The correlation is not very strong (R^2~0.4), but visible. All tier 1 countries in 2012 are above average – with the exception of Austria. When the seven countries chosen separately are analysed, a correlation between performance and public subsidies does not exist (R^2 = 0.06).

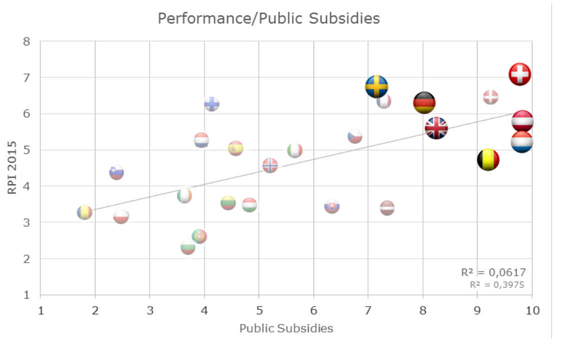

Figure 11 Performance and Public Subsidies (according to BCG [14])

Even though this correlation is not surprising, some points still apply. The public subsidies are addressed to inhabitants. Due to all financing boundary conditions, it is obvious that high transport volumes should lead to higher subsidies. In order to incorporate the transport volume instead of inhabitants, the subsidies are assigned to "operated track-km". On the one hand, this indicator considers the track lengths in the different countries. On the other hand, the amount of traffic (passenger train-kilometres and tonne-kilometres for freight) was normalised and used for the comparison. Even though this is a very rough harmonisation, the output indicator is much more cost-related than simply the number of inhabitants. Data used for these evaluations are published in the Commission's report on monitoring development of the rail market [16][17]

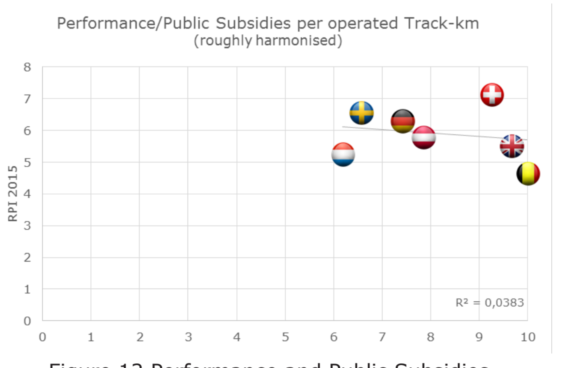

Figure 12 Performance and Public Subsidies
(Subsidies based on Network Size and Transport Volume)

Figure 12 shows that there is no correlation between the BCG performance index and the total amount of public subsidies if network length and operated trains are considered.

In 2015, BCG focused on this result and provided more in-depth information concerning the public subsidies by dividing the subsidies into infrastructure-related and train service-related. The study compares the relative value for money ratio with the percentage of public subsidies allocated to the infrastructure (note: The Value for Money Rating includes public subsidies per inhabitant once more). There is no strong correlation again, but a trend can be observed (Figure 13).

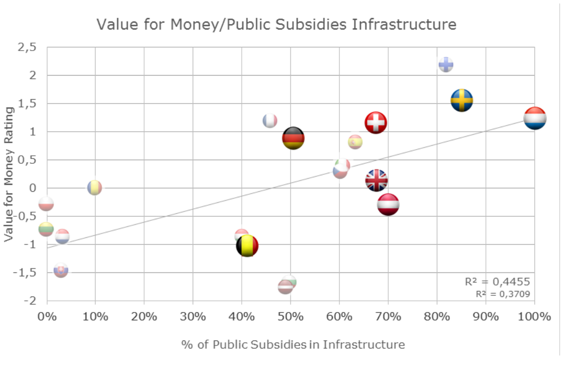

Figure 13 Value for Money Rating and Public Subsidies Infrastructure (according to BCG [14])

The conclusions drawn by BCG are courageous: BCG advised public subsidies to be allocated predominantly to the infrastructure in order to receive the highest value for money. The line of argumentation that higher subsidies in the infrastructure would lower track access charges and therefore enhance the economic scope of RUs to offer train services is easy to follow. In any case, the performance is only slightly affected. Dividing the RPI into its three indicators and correlating them with the public subsidies into the infrastructure produces clear results:

- Investments increase the safety level (as long as they are allocated to the existing network).
- Infrastructure subsidies do not increase the intensity of use, but intensive use requires higher public subsidies as long as track access charges do not recover the full cost (see later).

- The quality of service indicator does not correlate with subsidies at all – neither with infrastructure subsidies nor with subsidies to the RUs. Both cases show negative correlations. That would indicate that higher public subsidies decrease the quality of service. As this is very unlikely, the indicator itself might be the problem.

Adjusting the Value for Money rate according to Figure 12 produces different conclusions: Figure 14 shows that there is no correlation between Value for Money and the percentage of public subsidies going to the IM. Absolute values are different in some cases; different sources of data might be the reason, but this does not influence the general result. The only statement that can be made is that the highest performance can be achieved if there is a good balance between subsidising RUs and IMs. However, there is no proof for such a conclusion.

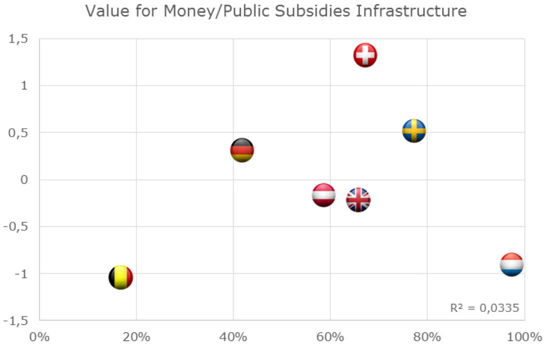

Figure 14 Value for Money Rating and Public Subsidies Infrastructure
(Subsidies based on Network Size and Transport Volume)

Obviously, the interfaces between the Railway Undertakings and Infrastructure Manger is relevant for the performance of the railway system, as well as the one between the Infrastructure Manager and Public Authorities. Both these interfaces are therefore analysed in a little more detail.

1.4.3 Assessing the Interface Infrastructure Manager – Railway Undertaking

The organisational interface between the IM and RUs is defined quite clearly in juridical terms: The network statement equals the terms of use of the infrastructure. The IM provides the infrastructure and allocates the capacity to the RUs. If the IM is not independent in its decision-making, the latter part could also be carried out by a separate body. The RUs pay a charge for the infrastructure use (see chapter 1.5 for details). Both train path allocation and access charging must be non-discriminatory and fair. In case of conflicts, the regulatory body functions as a mediator. This legal framework and its practical aspects are covered by the liberalisation index (see chapter 1.4.1). Table 1 shows the most relevant aspect of this is the charging scheme, with an 18% input on the total LIB index.

This charging scheme is defined generally in the EU regulations (see chapter 1.5), but is far from being a sufficiently described and harmonised interface. Figure 15 shows the differences in charges for average trains for seven countries. Not only the absolute values differ in a wide range, but also the proportion between freight and passenger services are different. These charges contain the direct costs as well as mark-ups. Seen from a theoretical point of view, it is astonishing that costs and/or the economic situation ("what the market can bear") differ so much throughout Europe, and especially in the countries analysed – which are "railway-affine" countries in any case. (For more information on TACs, see chapter 1.5.)

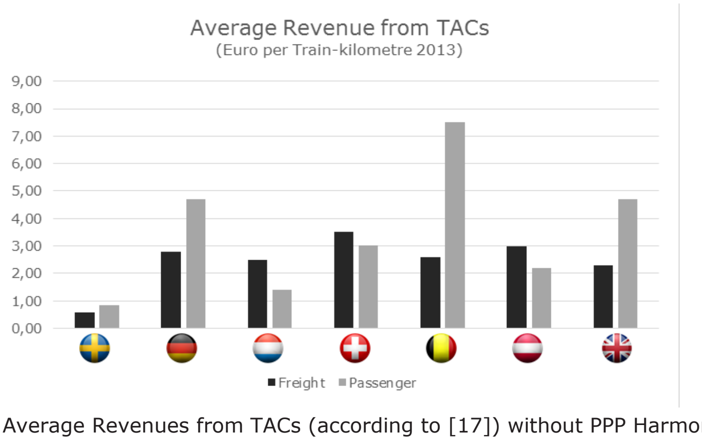

Figure 15 Average Revenues from TACs (according to [17]) without PPP Harmonisation

Two main topics of railway operation are not sufficiently defined by the juridical framework, although they are critical for the overall system cost and therefore also performance:

- An optimised use of the capacity provided is linked to an optimised timetable. This fairly strict regime might not fit the RU's demands. In particular, when it comes to an integrated timetable for passenger services, guaranteeing the best offer for the customer in minimising travelling time from A to B, the open-access policy is a challenging boundary condition. This topic is not part of the present analyses, but should not be neglected.
- The performance of the wheel-rail contact is triggered by the adjustment of these two contact partners. What happens technically at the small contact patch of wheel and rail is a topic in itself – and a challenging one. The juridical framework and the attached normative regulation (especially TSIs) can only focus on a certain level, which is defined to be safety-relevant. Consequently, these regulations have defined limit values (maximum axle load, maximum lateral forces, maximum track geometry failures, etc.). The limits are far from being optimal in terms of wear and tear (damage). Optimisation therefore happens on the "wheel part" (RUs) and on the "rail part" (IM), leading to two sub-optima.

The RU-IM interface is strongly influenced by political decisions within every Member State. Being financial and technical interface, TACs are regulated by the public authorities and not by the IM.

1.4.4 Assessing the Interface Infrastructure Manager – Member State

In an analysis of the business situation of infrastructure managers, it becomes apparent that – this is, of course, simplified – three sources of income exist: state grants, track access charges (all business actions related with the railway operation), and other businesses (energy business, renting of station areas, etc.). The proportions of these sources of income vary widely within Europe (Figure 16).

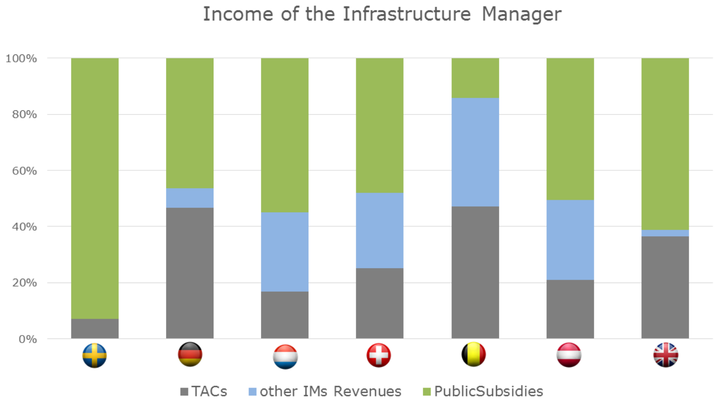

Figure 16 Income of the Infrastructure Manager [17]

The total amount of money covered by TACs (including mark-ups) depends strongly on the amount of public subsidies. As direct costs (wear and tear costs) should be more or less equal, this must be allocated directly to the mark-ups. The hypothesis "The amount of public subsidies assigned to the infrastructure defines the height of the mark-ups" is proven by Figure 17.

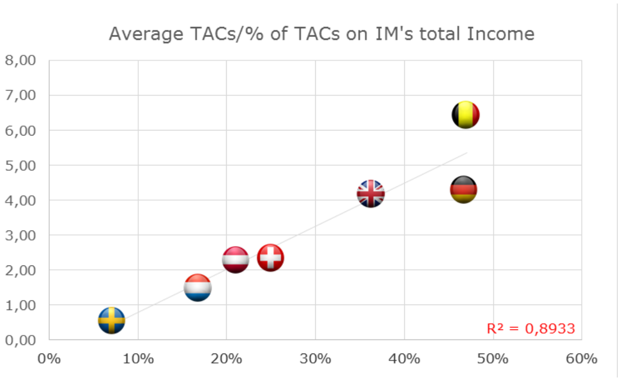

Figure 17 Correlation of Average TACs and TACs to Total IM Income (PPP Harmonisation)

A high income by TACs would indicate that the market is able to bear high mark-ups. This hypothesis is relativised by also considering the public subsidies allocated to the passenger traffic. Figure 18 shows the proportions of public subsidies allocated to the infrastructure, on the one hand, and to the passenger traffic, on the other.

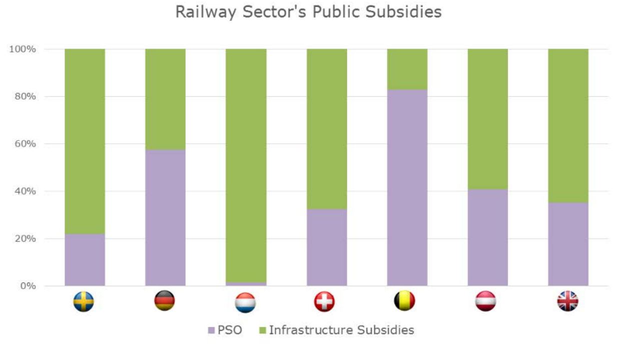

Figure 18 Public Subsidies [17]

An obvious conclusion is reached when average track access charges for passenger trains (in € per train-kilometre) are compared with the percentage of public subsidies to passenger traffic: A high percentage of PSOs allows high track access charges for passenger trains and vice versa.

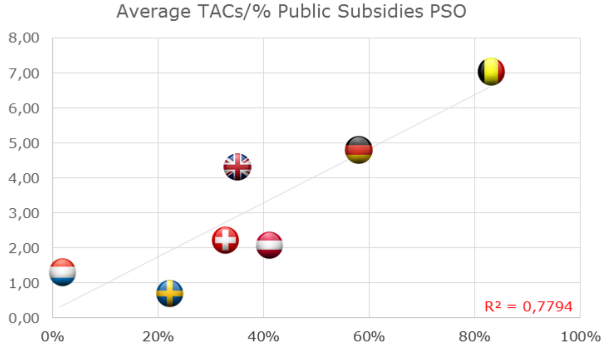

Figure 19 Average Passenger Train TACs (PPP Harmonised) and PSO Percentage of Total Public Subsidies

For freight transport, the situation is different (Figure 20). TACs do not differ much from the average TACs for a freight train-kilometre (PPP harmonised, median = €2.45/km), with the exception of Sweden.

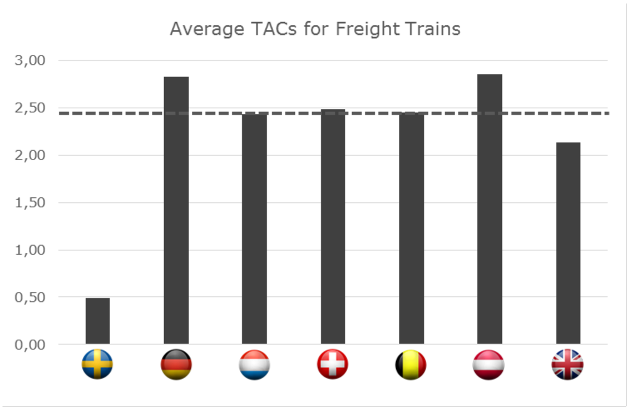

Figure 20 Average Freight Train TACs (PPP Harmonised)

Austria's and Germany's higher charges can be justified by their high volumes of freight traffic on rail (Figure 21). The same is true for the UK's lower charges. In the Netherlands, freight trains have to bear a high charge compared to the market situation. Sweden is a different case, however.

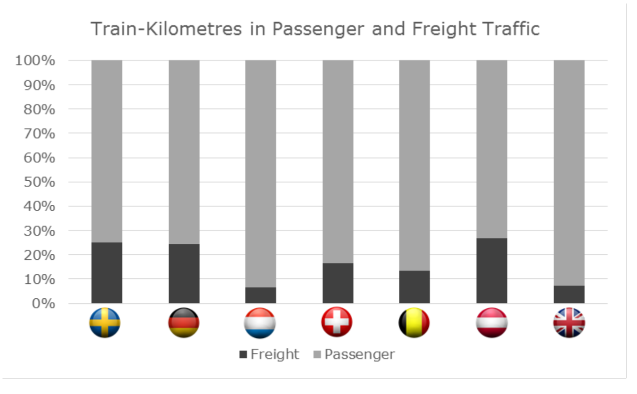

Figure 21 Percentage of Freight Traffic

In a very brief summary: The financial situation of the railway system, and therefore of the IM, is very different throughout Europe. The transport policy of every Member State, in particular, has a strong impact on the absolute amount of track access charges.

1.5 Track Access Charges – Legislation and Reality

Track access charges (TACs) are the main focus of this paper. Since the basic principles have already been covered in chapter 1, this chapter will consider the topic in more detail. As a first step, the legislation is analysed. European railway policy was implemented in stages as described below. In addition, the definition and scope of TACs has been changed over the years. With the implementing act 2015/909 [18], a precise rule on the assessment of the *"cost that is directly incurred as a result of operating the train service"* is now in place. The need for this detailed description is a result of misinterpretation, misunderstanding, and neglecting what had been published in the preceding years.

1.5.1 Track Access Charges in the Legislation from 1991 to 2015

TACs were subject to several directives published since 1991:

- Council Directive 91/440/EEC on the development of the Community's railways [2]
- Council Directive 95/19/EC on the allocation of railway infrastructure capacity and the charging of infrastructure fees [3]
- Directive 2001/14/EC on the allocation of railway infrastructure capacity and the levying of charges for the use of railway infrastructure and safety certification [6]
- Directive 2012/34/EU establishing a single European railway area (recast) [7]
- Commission Implementing Regulation (EU) 2015/909 on the modalities for the calculation of the cost that is directly incurred as a result of operating the train service [18]

The regulations are discussed in the following chapters. The focus here is on significant changes and additional topics that were added over the years.

1.5.1.1 Directive 91/440

The main objective of Directive 91/440 [2]is to separate infrastructure operation and train operation. Access charging is only mentioned as a side note. The Directive defines that the user fee is to be paid by the RU to the IM, and that the Member States are responsible for the rules that establish the charges.

The second paragraph of Section III, Article 8 states that: *"The user fee, which shall be calculated in such a way as to avoid any discrimination between railway undertakings, may in particular take into account the mileage, the composition of the train and any specific requirements in terms of such factors as speed, axle load and the degree or period of utilization of the infrastructure."* While this is very general in terms of the absolute height of the charge, it is very technical. The main influencing parameters such as speed and axle load are mentioned, as well as the train type itself. This formulation can be seen as the basic definition of the marginal cost principle.

1.5.1.2 Directive 95/19

Directive 19 from 1995 [3] focused on the topic of capacity allocation and charging. It defines in much more detail what was omitted in 1991. In addition to the financial situation of the infrastructure manager (at least balanced accounts by charges plus state contributions), it again states that the Member State is responsible for the general rules.

Section III, Article 8, states that *"The fees charged by the infrastructure manager shall be fixed according to the nature of the service, the time of the service, the market situation and the type and degree of wear and tear of the infrastructure."* This sentence includes what has basically been law up to now. The charge can (or shall) include the marginal costs (wear and tear), the demand of a train service ("nature"), possibly surcharges or reductions for times of high or low capacity demand, and the market situation of the RUs (mark-ups). According to the Directive, charges must be fixed, which means published in advance. This is an important aspect for the RUs, as charges are an input parameter of their business cases.

1.5.1.3 Directive 2001/14

This Directive [6], together with Directives 2001/12 [4] and 2001/13 [5], forms the first railway package. This package can be seen as first step towards a liberalised system based on an open-access infrastructure used by competitive train operating companies (see chapter 1.2.2). The key aspects of the Directive are capacity allocation, levying of charges, and safety certification.

Compared to what had previously been envisaged for user fees, the Directive goes into much more detail and introduces new aspects to the topic of charging. The general rule of fair and non-discriminatory access to the infrastructure is also indicated for the charging. Chapter II, Article 4, paragraph 5 states that *"Infrastructure managers shall ensure that the application of the charging scheme results in equivalent and non-discriminatory charges for different railway undertakings that perform services of equivalent nature in a similar part of the market and that the charges actually applied comply with the rules laid down in the network statement."* Following the marginal cost (wear and tear) approach, it is important that the adjective "equivalent" is not interpreted as "same".

Article 7 sets out the nine principles of charging. The following are important and new:
3. "… the charges for the minimum access package and track access to service facilities shall be set at the cost that is directly incurred as a result of operating the train service."
4. "The infrastructure charge may include a charge which reflects the scarcity of capacity of the identifiable segment of the infrastructure during periods of congestion."
5. "The infrastructure charge may be modified to take account of the cost of the environmental effects caused by the operation of the train. Such a modification shall be differentiated according to the magnitude of the effect caused."

The distinction between the minimum access package, service facilities, and other services is new. While additional and auxiliary services that are not essential to operate a train are free to be set at any price, the minimum access package *"shall be set at the cost that is directly incurred as a result of operating the train service"*. The cost "directly incurred" has been discussed intensively since the Directive was published. The easiest way to understand this cost definition is still the marginal cost approach. It must be noted, however, that this marginal cost level should be the standard case, according to Directive 2001/14.

In most countries, this is not the case, and never has been. Charges are set to a level that Article 8 (*"Exceptions to charging principles"*) allows. It states that *"in order to obtain full recovery of the costs incurred by the infrastructure manager a Member State may, if the market can bear this, levy mark-ups on the basis of efficient, transparent and non-discriminatory principles…"*. The Directive does not specify who is in charge of deciding how much mark-up the market can bear. It only mentions that *"the level of charges must not, however, exclude the use of infrastructure by market segments which can pay at least the cost that is directly incurred as a result of operating the railway service, plus a rate of return which the market can bear."*

Paragraph 3 of Article 8 slightly relativises what has already been stated regarding equivalent charges. It states that it is necessary to ensure that *"comparable services in the same market segment are subject to the same charges."* The meaning of "comparable" remains open. Considering a regional passenger train service, is it comparable if a locomotive wagon train or an EMU provides this service? In terms of wear and tear, it is definitely not comparable. From a technical point of view, these two trains are not comparable.

Article 9 focuses on discounts that should not be granted in standard cases. Only in the case that *"schemes (are) available to all users of the infrastructure, for specified traffic flows, granting time limited discounts to encourage the development of new rail services,* *or discounts encouraging the use of considerably underutilised lines"* can discounts be provided. This does not affect the general rule that charges should at least recover the marginal costs.

An interesting topic is discussed in Article 10 *("Compensation schemes for unpaid environmental, accident and infrastructure costs"*). It deals with time-limited compensation schemes for rail services for the unpaid costs of competing transport modes. This makes it possible to consider the lower external costs of railway transport compared with other transport modes, especially the road mode. Such discounts would reduce charges, of course.

In order to incentivise both IM and RUs to "minimise disruption and to improve the performance of the railway network", Article 11 introduces a so-called performance scheme. This scheme insures payments to the IM or the RU whenever either of them causes disruption or delays.

Article 12 opens the possibility of charging for reserved but not operated train slots in order to incentivise an optimal use of the capacity provided.

According to this framework, TACs have been installed in the Member States. As most of the charges are optional, a wide variety of charging schemes was the consequence. One important aspect was not taken into consideration by the IMs and the Member State authorities in charge for the general rules: the distinction between marginal costs for the minimum access package and the mark-ups. Most IMs did not and do not publish them separately, but set different prices for different services and/or lines.

1.5.1.4 Directive 2012/34

Known as the recast of the first railway package, Directive 2012/34 [7] summarises the topics of the first railway package and therefore provides a revision of Directives 2001/12 [4], 2001/13 [5], and 2001/14 [6]. In terms of track access charges, Section 2 of Chapter IV is relevant.

One new aspect is the incentive that should be provided to the IM to reduce the level of charges (Article 30). Additionally, a proper register of the IM's assets and a cost accounting system must be set in place. These tools must be used to allocate the costs to the different users. The Member States (or Regulators) may require approval, while the allocation method is open to updates.

Article 31 states that charges of the minimum access packages may include charges reflecting scarcity of capacity, and may be modified due to environmental effects. A special topic in paragraph 5 of this article is noise-differentiated charging. This idea is targeted at freight traffic, as the Directive points out: *"Any such modification of infrastructure charges to take account of the cost of noise effects shall support the retrofitting of wagons with the most economically viable low-noise braking technology available."*

The mark-up issue is dealt with in Article 32. The new task of the IM is thereby to *"evaluate their relevance for specific market segments"*. The minimum requirement is to distinguish between *"freight services, passenger services within the framework of a public service contract and other passenger services."* Furthermore, *"Infrastructure managers may further distinguish market segments according to commodity or passengers transported."* This new responsibility seems to exceed the IM's position in the railway system. On the one hand, there is a strong relationship between necessary mark-ups and public subsidies to RUs covering PSOs (see Figure 19) in order to reach balanced accounts. How much mark-up can a subsidised passenger train service bear? On the other hand, freight and non-subsidised passenger traffic may bear a certain amount of fixed infrastructure costs. However, as the infrastructure owner, it should be the Member State's obligation to set these mark-ups. By defining a certain amount of subsidies for the IM, the Member State also defines the total amount of mark-ups to be charged.

1.5.1.5 Implementing Regulation 2015/909

Regulation 2015/909 [18] defines *"the modalities for the calculation of the cost that is directly incurred as a result of operating the train"* announced by Directive 2012/34. The Regulation is expected to provide answers to unsolved topics. Article 3, paragraph 1 gives an idea of the absolute height of the direct cost on an averaged network-wide basis: *"Direct costs on a network-wide basis shall be calculated as the difference between … the costs for providing the services of the minimum access package … the non-eligible costs".* Paragraph 4 is important, as it directly addresses costs: "*… if the infrastructure manager can transparently, robustly, and objectively measure and demonstrate on the basis of, inter alia, best international practice that costs are directly incurred by the operation of the train service, the infrastructure manager may include in the calculation of its direct costs on a network-wide basis in particular the following costs:*
(a) costs of staff needed for keeping open a particular stretch of line if an applicant requests to run a specific train service scheduled outside the regular opening hours of this line;
(b) the part of the costs of points infrastructure, including switches and crossings, that is exposed to wear and tear by the train service;

(c) the part of the costs of renewing and maintaining the overhead wire or the electrified third rail or both and the supporting overhead line equipment directly incurred as a result of operating the train service;
(d) the costs of staff needed for preparing the allocation of train paths and the timetable to the extent that they are directly incurred as a result of operating the train service."

This is the clearest definition of what "costs directly incurred as a result of operating the train service" could be, since track access charges were mentioned with this wording in the EU legislation. The cost of track wear is missing, although this is obviously linked to a train run.

Article 5 on the *"Calculation and modulation of direct unit costs"* states in paragraph 1: *"The infrastructure manager shall calculate average direct unit costs for the entire network by dividing the direct costs on a network-wide basis by the total number of vehicle kilometres, train kilometres or gross tonne kilometres forecasted for or actually operated."* And further on: *"Alternatively, if the infrastructure manager demonstrates to the regulatory body … that the values or parameters … are significantly different for different parts of its network, and after splitting its network into such parts, the infrastructure manager shall calculate average direct unit costs for the parts of its network by dividing the direct costs for these parts by the total number of vehicle kilometres, train kilometres or gross tonne kilometres forecast for or actually operated."*

While this defines a procedure to calculate the total network-wide direct costs, the Regulation goes into the technical aspect in much more detail: *"The use of vehicles or railway lines with certain design features results in different levels of direct costs incurred by the train service. Member States may allow their infrastructure managers to modulate average direct costs in accordance with, inter alia, best international practice to reflect such differences."* The Commission is aware of the fact that not all IMs may be in a position to calculate direct costs on this level: *"Different forms of econometric or engineering modelling might offer a higher degree of precision in calculating direct costs or marginal costs of the use of infrastructure. However, cost modelling requires a higher level of data quality and expertise than methods based on deducting from the full costs certain non-eligible cost categories."*

Article 5, paragraph 2 lists vehicle and track parameters according to which "Member States may allow the infrastructure manager to modulate the average direct unit costs". The parameters are

(a) train length and/or number of vehicles in the train;

(b) train mass;

(c) type of vehicle, in particular its unsprung mass;

(d) train speed;

(e) traction power of the motorised unit;

(f) axle weight and/or axle numbers;

(g) recorded number of wheel flats or the effective use of equipment to protect against wheel slips;

(h) longitudinal stiffness of vehicles and horizontal forces impacting on the track;

(i) consumed and measured electric power or the dynamics of pantographs or contact shoes as a parameter to charge for the wear and tear of the overhead wire or the electric rail;

(j) track parameters, in particular radii;

(k) any other cost related parameters where the infrastructure manager can demonstrate to the regulatory body that values for each such parameter, including variation to each such parameter where relevant, are objectively measured and recorded.

The list includes most cost drivers of track (and catenary) costs. Surprisingly, wheel flats are mentioned. It is a basic principle of track access charging that charges must be foreseeable for the RUs. Wheel flats must be measured on wayside track monitoring systems and could therefore only be charged after the run of the train, as a surcharge.

Paragraph 3 notes that a *"modulation of the direct unit costs shall not result in an increase of the direct costs on a network-wide basis…"*.

Directive 2012/34 [7] foresees that the regulatory body controls the TAC scheme. Article 7 on *"Simplified control"* adds a procedure supporting the regulator's decision if direct costs are controlled in detail or simplified. Paragraph 1 states that: *"If direct costs on a network-wide basis … are equivalent to either less than 15 % of the full costs of maintenance and renewal or less than the sum of 10 % of maintenance costs and 20 % of renewal costs, the regulatory body may carry out the control … in a simplified manner."* However, the limits are weak, as *"Member States may decide to increase the percentages mentioned in this paragraph to not more than twice the indicated values."* Paragraph 2 defines how the regulatory body should handle modulation*: "The regulatory body may accept the calculation … if the average direct costs per train kilometre of a 1 000 tonne train amounts to not more than EUR 2 (at 2005 prices and exchange rates, using an appropriate price index)."* Considering what is analysed in chapter 1.4.4 and chapter 0, this €2 limit seems a little strange. On the other hand, it helps the regulatory body to decide whether a detailed control is necessary or not.

1.5.1.6 Summary and Discussion – Legislation

At present, TACs must be calculated at the direct cost level. The procedure is defined in Regulation 2015/909 [18]: Calculation on a network-wide basis (or several parts of the network if necessary) to provide average figures (for the regulator's control). These costs can be modulated using econometric or engineering models. The modulation parameters listed allow a detailed calculation.

Additional effects (scarcity charges, environmental charges) could be considered within the direct costs. This seems to be somehow inconsistent: Direct costs should be based on the cost-by-cause principle. Scarcity of capacity can influence the cost level to a certain degree, but is not actually linked with any damage process.

A performance scheme is mandatory. It should apply for both the RU and the IM, and should incentivise efforts to minimise system fallouts.

Mark-ups must be calculated for pairs of rail traffic (passenger vs freight, regional passenger vs long-distance passenger, PSO traffic vs non-PSO traffic, etc.). The IM is obliged to have economical proof that the market (segments) can bear this profit margin. It is actually neither the IM nor "the market" that defines the necessity or height of mark-ups, but the Member States (see 2.1).

1.5.2 Track Access Charges throughout Europe

New legislation is in place to change the requirements of the charging schemes. This will have a strong impact on the TACs within the European Union. While the principle of marginal costs and mark-ups is not new, the majority of TACs do not report direct costs separately and if they do, the costs incorporated are not compliant with Regulation 2015/909 [18].

Generally, it can be stated that the overwhelming part of the charging systems in Europe is not based on costs, but on "what the market can bear". This explains the strongly varying absolute values of TACs, but also the different balances between passenger and freight trains. To sum up very briefly:

CEO countries have comparably high charges, especially in freight transport, although cost levels are well below the average. The (freight) market can definitely not bear the payload and shows shrinking modal split figures. Mark-ups must be kept high (up to full cost recovery) as state funding is not sufficient to finance the IM's obligations.

Scandinavian TACs are very low. The IMs charge below marginal costs to support the railway traffic. On the other hand, the subsidies for passenger traffic are low (see Figure 18).

Countries with high-speed passenger traffic have very high prices for high-speed trains. These high charges allow other charges to remain low.

Figure 22 illustrates these findings. Freight charges are much more balanced. Without including Estonia, the medium deviation of the median value is only 13%. In passenger charges, the variation is much higher (more than 70% from the median). This topic was already discussed in combination with PSOs.

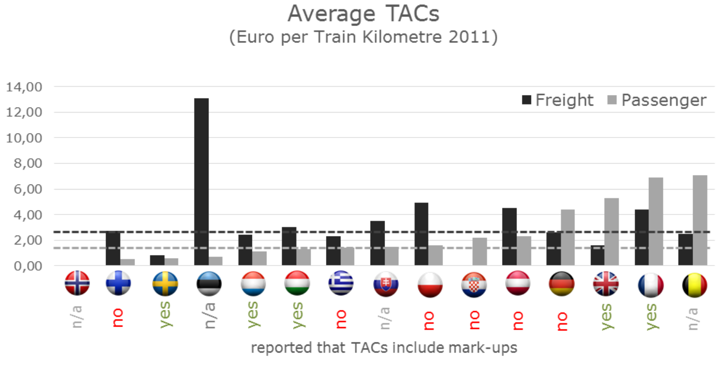

Figure 22 Average TACs in Europe [19]

What is very interesting is the interpretation of the direct costs. Figure 22 also provides the IMs' answers to the question of whether mark-ups are included in their TACs. The most interesting answers come from Austria and Germany, on the one hand, and Sweden, on the other: While the former two countries reported that they had not charged mark-ups although they had a high level of charges, Sweden reported that it had charged mark-ups although it had the lowest level of charges in Europe. This evaluation explains why Regulation 2015/909 [18] was necessary.

The same situation occurs in other aspects of TACs. Scarcity of capacity/congestion, slot reservation, environmental effects, etc. are charged in one country, but not in another, and vice versa.

The UK is the only country to distinguish between variable access charges (VAC) and fixed charges (mark-ups/concessions) to date. The VAC are vehicle-specific, and are currently the only wear-based track access charging scheme in Europe.

1.6 Summary – Effects and Gaps

It is questionable whether the liberalisation of the railway system is the right way to increase the popularity of this transport mode again. Although some very liberalised countries face rising traffic volumes, this is also true for some that are not very liberalised. This is mostly due to the rising transport sector in general. At a European level, changes in the modal split are not significant. It appears that the decline of the railways has stopped, at least (Figure 23).

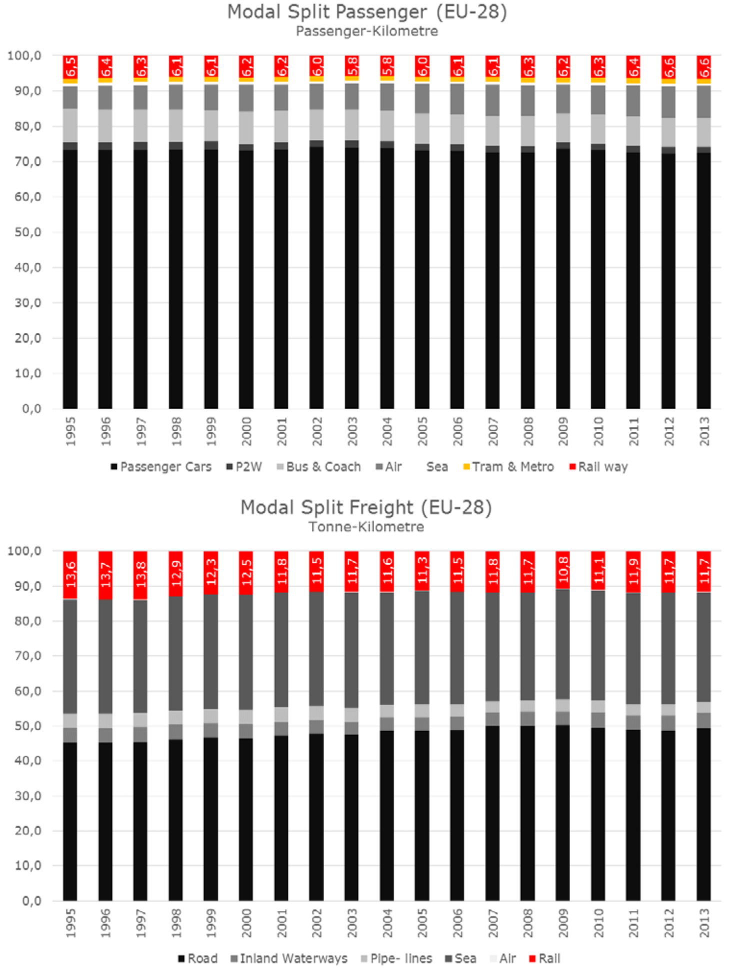

Figure 23 Modal Split EU-28 – Passenger & Freight [20]

The separation of RUs and IMs definitely made the situation more complex. The multiple organisational interfaces create more problems than they solve. If the IM's tasks are outsourced, additional interfaces and problems occur. Since general transport policy is not the topic of this paper, the work focuses on the part of the infrastructure costs that is influenced by a train run. The EU legislation defined these costs as direct costs or *"cost that is directly incurred as a result of operating the train service"*. Although the topic of mark-ups is considered again very briefly (chapter 0), the main idea of this paper is to indicate technical interfaces that must be transcribed into costs (or charges) in order to keep the system working properly and to provide room for technical improvement. Only technical improvement enables overall system costs to be decreased and therefore guarantees the competiveness of the transport mode railways.

One of the major gaps in the European railway system should be highlighted: the case of innovative vehicle technology. Since RU have their own accounts, they only include what appears as prices or internal costs in their business cases. In the event of a vehicle procurement process, a business case is set up, consisting of five main financial inputs: vehicle investment cost (price of the vehicle producer), vehicle maintenance costs over the entire lifetime, operational costs, track access charges, and revenues from the customers. The result of this general business case is the decision on whether to operate the train service or not. If different vehicle options are analysed, only the first two cost inputs change if track access charges are calculated on the basis of train-kilometres. If TACs are calculated on the basis of gross-tonne-kilometres, they vary in terms of the vehicle weight, at least.

In reality, the situation is different. Vehicle parameters influence the damage processes. A reduction of unsprung masses or a radial steering bogie cannot be described by charges based on train-kilometres or gross-tonne-kilometres, although both measures save maintenance costs on tracks due to reduced wear. If savings in vehicle maintenance exist and do not justify an additional investment in better and track-friendly technology, the RU simply has no incentive and no business case to purchase such technologies, even though it would be beneficial when considered at the level of the railway system.

Even larger problems occur if this is analysed for excessive-wear vehicles. The economic signal of weight-driven or train-kilometre-based TACs to the RU is a simple one: The only thing that counts is the weight (or the train run). Accordingly, the RU's specification for the vehicle is very simple. The cheapest vehicle for the purpose of the train service is the best one. While the RU side is optimised, the loss due to higher infrastructure expenditure is covered by the IM.

This is, of course, short-term thinking. The decisions made based on this short-term thinking have consequences for an entire service life, 30 or 40 years. The suboptimization leads to higher system costs in the end. Creating low-cost vehicle technology induces high-maintenance tracks. The gross-tonne-kilometre or train-kilometre charge increases from a mid-term perspective, due to higher wear, and all the RUs have to cover the additional infrastructure costs.

Track access charges are one of the most critical interfaces introduced by the open-access principle. If they do not transfer the (technical and cost) consequences of decisions from one stakeholder to the other, they provide the wrong economic signals and therefore induce higher system costs.

This technical logic is not influenced by the total public subsidies for either the infrastructure or the train operation. It is a matter of *"cost that is directly incurred as a result of operating the train service"*. Consequently, this paper tries to provide methodology to calculate and allocate the direct costs detailed as necessary to cover the interaction. Technical improvement and the consecutive system optimisation must be based on a properly functioning organisational and financial interface.

2

Infrastructure and its Cost

There are two aspects to this topic: the financing of the IM’s business and the total money spent. The IM’s income has to balance its costs consisting of expenditure for maintenance, renewal, operation, and overheads.

When the total budgets are recalculated to operated track kilometres (including a rough harmonisation by using the total number of regional and long-distance passenger trains and the amount of carried tonnage in freight traffic), the costs differ significantly from country to country:

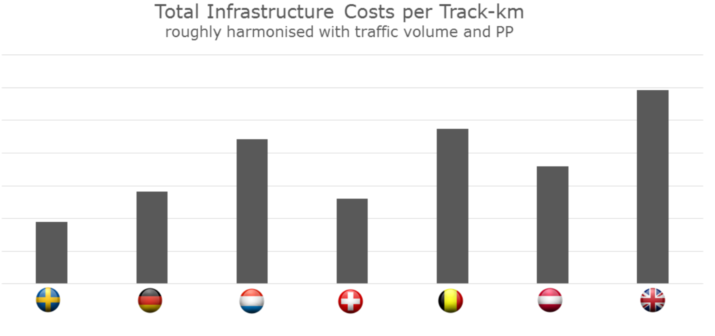

Figure 24 Total Infrastructure Expenditure per Track-km [17]

There are numerous reasons for the large differences. The infrastructure of the railways is not a homogenous asset. This is true for the technical structure as well as for its costs. The following chapters provide an overview of the costs of different asset types.

Before going into the technical details, a major general topic is discussed: the general maintenance and renewal strategy of the IM or Member State. As this strategy is somewhat independent from the technical aspects, this strategy topic is considered at the beginning. All the following cost analyses (chapters 2.4) are based on a "sustainable steady state" in order to show the effect of different cost drivers independent of the strategy followed.

2.1 General Maintenance and Renewal Strategy

A major point of discussion is the proportion of maintenance versus renewal. While the renewal rate is linked directly with the average service life, the maintenance is sometimes difficult to determine. In theory, the economic service life (lowest life cycle costs/LCC) of an asset is reached when the incremental decrease of depreciation is lower than the incremental increase of maintenance. Figure 25 shows the depreciation as a function over time (green curve). The decrease is fast in the initial years (not pictured) and slows down with longer service lives due to the 1/n-function. Maintenance (yellow line) increases slowly at the beginning (young asset) and more quickly at a certain age of the asset. The optimal point in time for the renewal is reached when

$$\frac{dD}{dt} \equiv \frac{dM/a}{dt} \qquad \text{EQ 1}$$

with
D Depreciation
M/a Maintenance per year
dt Increment of Time

While the service life therefore differs from asset type to asset type, and within one asset type, due to different boundary conditions, the cost link in Figure 25 is always true.

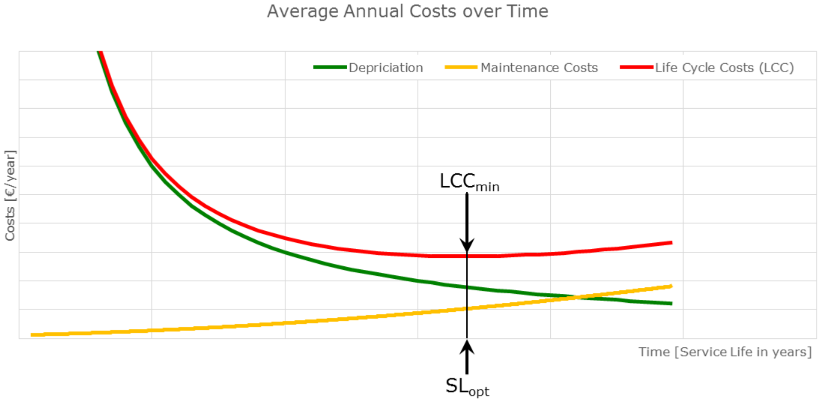

Figure 25 Minimised LCC and Optimal Service Life

When the optimal service lives for all assets of one type are averaged, the renewal rate for this asset type can be calculated easily by

$$\text{Renewal rate} = \frac{\text{Total amount of assets [km, \#, m}^2\text{,...]}}{\varnothing\ SL_{opt}\ \text{[years]}}\ \text{[km, \#, m}^2\text{,.../a]} \qquad \text{EQ 2}$$

Summarising the renewal demand of all asset types by multiplying them with the specific unit costs determines the renewal budget. Maintenance demand is directly linked to this renewal rate as a certain amount of maintenance is assumed within the calculation of the optimal service life. Every change in this equilibrium effects the total costs (Figure 26).

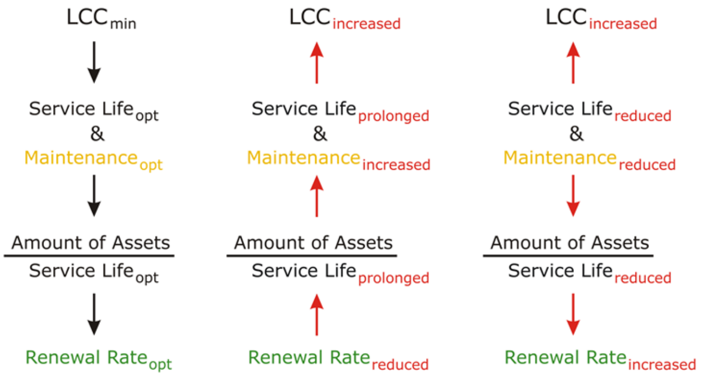

Figure 26 LCC, Renewal Rate, and Maintenance

These dependencies are important in discussions of marginal infrastructure costs: TACs do not recover the total cost of the IMs and budgets of the Member States are under pressure from time to time. Short-term savings (or quick wins) could be desirable or necessary. There are three options to create these savings:

(1) Short-term savings in maintenance
(2) Short-term savings in renewal
(3) Short-term savings in maintenance and renewals

All three options (Figure 27) lead to an unsustainable situation and – from a long-term perspective – to a cost increase on a large scale. This is a consequence of the cost link shown before and will now be explained further. Note: For the following analyses it is assumed that a "sustainable steady state" shows renewal and maintenance expenditure of about the same height (with "maintenance" including inspection and time-bound maintenance as well) for an entire network and for all asset types in general. This reference case is marked with (0) in Figure 27.
In case (1), low maintenance leads to reduced service lives after a certain time, as the necessary quality level can no longer be guaranteed. Renewal demand increases constantly as more and more assets reach the earlier point of reinvestment. A steady state can only be reached by increasing maintenance to the necessary level. When the maintenance budget is kept constantly high, renewal rates decrease slowly again.

Case (2) shows cost consequences that are even more critical. If renewal rates are too low, the assets start becoming overaged. Maintenance in the end-of-life phase of the asset life is very costly, so maintenance demand increases rapidly. Even if the renewal rate is set back to what was once the optimal (or necessary) amount, maintenance remains high due to the existing backlog. This steady state puts a lot of pressure on the maintenance budget. Only higher renewal rates can reinstall a balanced age distribution in the network. Maintenance reduces slowly; the long return to the optimal steady state is very cost-intensive.
If maintenance and renewal budgets are cut down in the same time, case (1) and case (2) superpose: Case (3) leads to a steady state with both high maintenance and high renewal demand. This steady state is maintained for a long time as both the lost service time and the backlog must be equalised with very high renewal rates. If this case is reached, the network must be partly rebuilt.

Figure 27 Short-term Savings and Long-term Consequences

What appears to be a theoretical approach can be shown by analysing different infrastructure in Europe. The "Lasting Infrastructure Cost Benchmark" (LICB) by the UIC [21][22][23] compares maintenance and renewal expenditure of various European IMs since 1995. The following figures show anonymised IMs, even though the code is an open secret comparing different publications. The exception is Network Rail, as the UK authorities published various studies based on the LICB data [24][25] in order to analyse the cost situation in UK's rail market that got out of control after the breakdown of British Rail and the partly collapsed privatised infrastructure system.

The methodology of the benchmark is based on a harmonisation process in order to get rid of system-immanent differences between the infrastructure networks. The harmonisation steps include purchasing power parities (PPP), the degree of electrification, single vs multiple track, switch densities, and track utilisation. The technical parameters considered have a strong impact on the result (maintenance and renewal per track-kilometre). In addition to the degree of electrification and the turnout density (the amount of assets influences the cost height, of course), the degree of utilisation has an enormous impact on (direct) costs. In the case of single or multiple tracked lines, there are no differences in technical behaviour, but high differences between the unit costs due to worksite logistics, preparation works, etc. Single tracked lines are typically 40% more expensive than double-tracked ones.

In the end, the results are comparable, or at least should be comparable. The difficult part in benchmarking is to draw the right conclusions. The benchmark is analysed, bearing in mind the theoretical derivations discussed above (Figure 25 to Figure 27). Note: The results from the year 2000 and from the 2005 report are valorised with 2% inflation (average over the years 1995 to 2010).

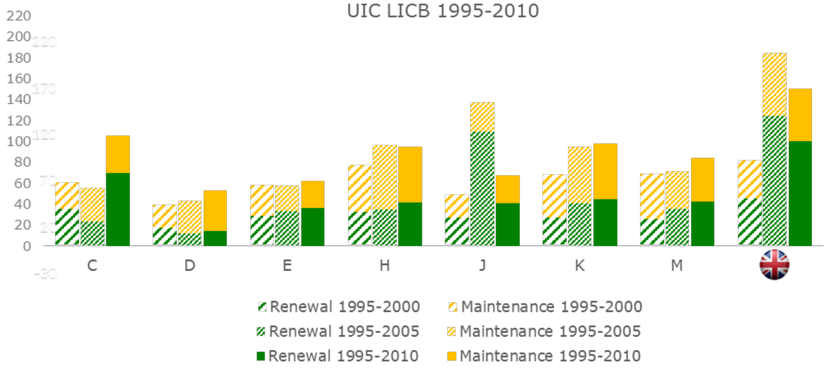

Figure 28 UIC Benchmark LICB

Figure 28 shows the benchmark result over the last 15 years. All IMs noted that the unit costs for renewals increased between 2005 and 2010 over average. This can be considered as taking a higher valorisation rate on the reinvestment costs (5% or more). Additionally, the renewal rate reported by IM J for the second period is neglected in the discussion, as it cannot be valid for statistical reasons. These two assumptions lead to the values depicted in Figure 29. Additionally, the medians of renewal and maintenance are added (grey bars in the background). They are calculated for the last evaluation with the 2010 figures.

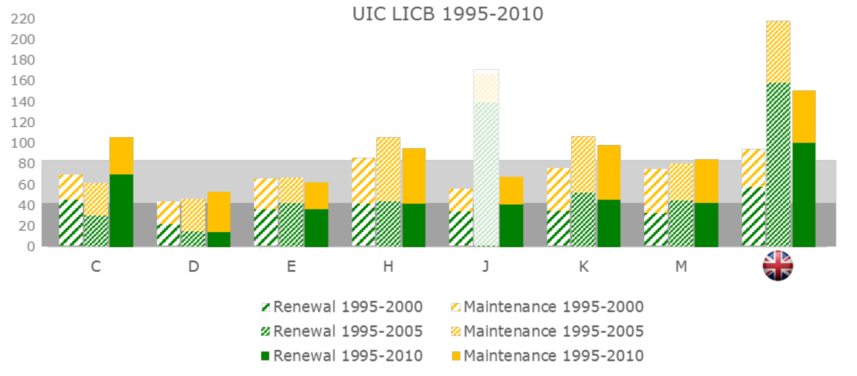

Figure 29 UIC Benchmark LICB – modified

In the countries H, K, and M the situation seems to be stable and sustainable, taking into account the deviations from the averages and the changes over time (and assuming that the average is sustainable, of course). The only difference seems to be the higher maintenance expenditures at the IMs in H and K. The infrastructure managers D, E, and J are below average and have unbalanced quotas of renewal and maintenance. As E and J have low maintenance, they will run into case (1) of Figure 27: reduced service lives and therefore higher renewal rates in future. As both are slightly below the average of renewal rates, a certain amount of backlog has already been generated. IM D has both low maintenance and low renewal rates, while maintenance is already increasing. This is an example for case (2) that first leads to exploding maintenance budgets and then to remarkable reinvestments to overcome the backlog. Network Rail and IM C face unsustainable situations. While C obviously starts to pay for past short-term savings with high renewal rates (first period case (1), second period case (3)), in the UK the reinvestment demand is two to three times higher than in the other countries. With a maintenance budget right at the average, this situation will continue for some time. This is a typical case (3): Network Rail must pay for past savings. The renewal and maintenance rates in the early 1990s will cause difficulties for the IM for a long time.

Of course, not all the effects are covered in this very simplified explanation. There is also generally a large problem with efficiency in the UK, but this is also true for all the other IMs: Unit costs influence the total costs, of course. This is discussed in detail later in this chapter (2.2.6).

For this paper, the following conclusion is important: The direct cost are not only a result of the damage that occurs whenever a train runs over a track. The costs are highly sensitive to the general maintenance and renewal strategy followed. As these strategies vary throughout Europe, the direct costs – and therefore the TACs – must also vary. Differences of more than 100% in the maintenance expenditure (of which inspection is a major and stable part and which is not applicable for the direct costs) lead to the conclusion that direct costs will vary quite significantly. How this should fit with the €2.00 per train-kilometre limit defined in Regulation 2015/909 [18] is unclear. As the values in Figure 29 are PPP harmonised, the differences must be even higher. If they only vary with some percentages in the end, it can be assumed that the values are not strongly connected to costs.

2.2 Cost Drivers

Regarding the different assets of railway infrastructure, some topics are generally true in terms of costs. These aspects are discussed further on, both generally and in detail as concerns the single assets. The aspects discussed beforehand are

- Asset Age
- Topography and Topology
- Maintenance Regime
- Component Technology
- Rail-Wheel Interaction
- Unit Costs
- Infrastructure’s Quality Level

This list is, of course, not complete, and could be extended with many other effects, but it provides the main cost drivers. These cost drivers are discussed in detail in the following chapters.

2.2.1 Asset Age

The asset age triggers the maintenance costs. This effect is stronger for some assets than for others, but always exists. Taking a simple example, the deterioration of track alignment, this effect can be shown quite easily. Figure 30 depicts the loss of quality over time, combined with an increasing deterioration of the quality until the point of renewal (in this case, a ballast cleaning).

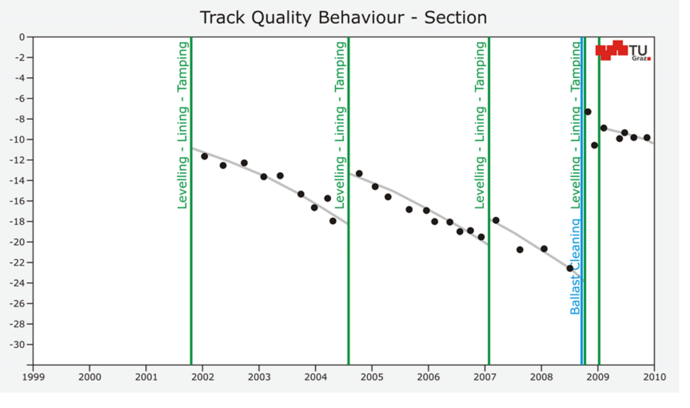

Figure 30 Track Quality Behaviour – Old Track

Having enough track section of different ages makes it possible to describe the quality behaviour over the entire service life. Figure 58 provides an example, whereby the green vertical lines are maintenance actions (tamping) and the red dotted line is the necessary minimum quality level (threshold value).

Figure 31 Track Quality Behaviour over the Entire Service Life

When analysing an entire network in a sustainable steady state, the age of the assets can be assumed to be equally distributed. In this case, older assets with more frequent maintenance and young assets with almost no maintenance need to be balanced. Although in the case of maintenance planning and decision-making, the increasing maintenance towards the end of the service life is crucial (see Figure 25), the equal age distribution guarantees a reasonable average when calculating the marginal cost level.

2.2.2 Topography and Topology

The topographical boundary conditions of a network define the costs of investment and maintenance to a very high degree. Railway lines in lowlands have almost no need for inclination and curves. In addition, tunnels are relatively seldom. Curved track leads to not only much higher maintenance costs, but also to a different kind of maintenance compared to straight sections. Service lives are generally lower due to higher loading, meaning that depreciation is much higher. A relevant part of the depreciation must therefore be dealt with as wear-related or "variable depreciation". Additionally, curves demand different technology. For the asset track, this topography is of high importance. The cost analyses later in this chapter indicate these clearly.

The topology of a country defines the infrastructure. The distance between areas of high population density, the relative importance of these areas within the country, the suburban and regional structure, and the topography (see above) form the boundary conditions for the design of a railway network. These boundary conditions are fixed or at least not easy to change. One example is the huge tunnel projects in Europe: If the topology leads to a certain transport corridor of high importance and the topography means that there is a difficult environment (mountains), expensive tunnels are the technical answer.

2.2.3 Maintenance Regime

Apart from the general maintenance and renewal strategy (chapter 2.1), the maintenance planning can be organised in different ways. The preconditions and consequences are depicted schematically in Figure 32. Highly sophisticated maintenance concepts require advanced knowledge of the deterioration processes and consequences of maintenance interference, and state-of-the-art technology, but can ensure that costs decrease.

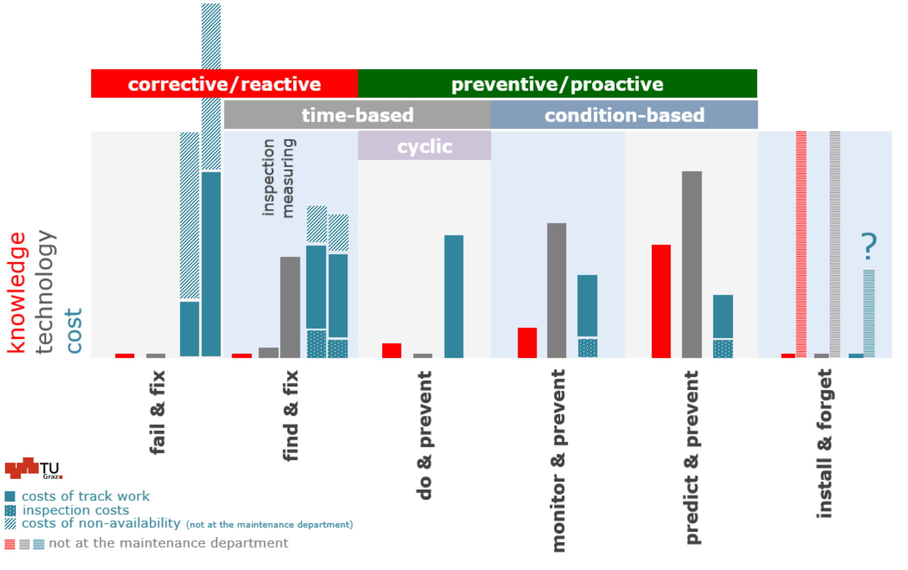

Figure 32 Maintenance Concepts

Corrective or reactive maintenance regimes lead to high costs in any case. The fail & fix concept means a very low number of interferences, of course, but if the system fails, repair costs are high (even higher if the entire technical structure is affected by the failure) and the downtime and the related costs (costs of operational hindrances, penalties) are very high. The find & fix concept, in which visual inspection (low technology demand) or measurements (high technology demand) detect failures before they might lead to a system breakdown is still corrective. Of course, this additional work adds costs (inspection costs), but reduces the negative consequences of a system interruption, in particular. Inspection-based maintenance is generally time-based maintenance.

Another time-based concept is the do & prevent regime, but it is preventive rather than corrective. Knowing the average time before a failure will occur allows a preventive maintenance action to be taken. Most of the time, this is a cycle maintenance concept (e.g. rail grinding after some millions of gross-tonnes). This is a common regime whenever the failure cause is not identified properly and measuring the results is not reliable (in track, e.g. the RCF topic). It leads to high maintenance costs and quite a high number of actions, but minimises the risk of system fallouts.

With regard to the condition-based maintenance regimes, the monitor & prevent concept is an advancement from the measuring-based find & fix concept. Analysing the trends of quality decrease over time makes it possible to intervene before the failure occurs. This results in better planning of maintenance actions and therefore reduces costs. The concept already requires a high degree of knowledge and technology. In a further step, the predict & prevent concept can be applied. Here, it is necessary to foresee the entire quality behaviour over time, including the consequences of maintenance actions. Knowing the optimal point of time for a maintenance action in order to guarantee the optimal balance between maintenance and renewal (calculation of the lowest LCC possible, see Figure 25) leads to the lowest overall costs. This maintenance concept is a vision for the future, since knowledge does not yet exist for most of the damage mechanisms.

Finally, there is also a maintenance concept that seems to be promising: the install & forget concept. If it is possible to install systems or components that are maintenance-free, the costs disappear, of course. The preconditions are highly improved knowledge and technology. The costs for such a concept occur in renewal. Whether the generally high investments are justified by maintenance savings over the total service life is subject to economic evaluations.

2.2.4 Component Technology

Even though the railway sector is not generally thought of as innovation-friendly, technological improvement exists and existed in the past. For example, track faced quite an intensive change of components within the last decades. While wooden sleepers and light rails (49E1) were still the standard solution back in the 1970s, nowadays tracks are constructed with a heavy superstructure consisting of 60E1 rail on concrete sleepers. Rail steel grade is still being improved to provide higher resistance: head hardening (heat treatment) is already standard technology, and research aims for higher steel grades. This list could be extended to include almost all components of railway infrastructure.

One aspect must, of course, be considered: As service lives of infrastructure assets are very long (25 to 80 years, or even more), the cost effects of improved technology only occur slowly throughout an entire network. “Old” technology is retained until it is economically justifiable to replace the assets, of course. On the other hand, increasing transport volumes reduce cost savings due to improved technology. This aspect cannot be neglected for total maintenance and renewal budgets, but it is irrelevant for the marginal cost.

The quality of the substructure is also very important for the asset track and will be considered in the section on track.

Examples for the cost impact of changed technology are provided in chapter 2.4.1.

2.2.5 Rail-Wheel Interaction

Without doubt, the rail-wheel interaction or – more generally – the vehicle-infrastructure interface determines the damage processes. Aspects subject to numerous studies and optimisation processes are seldom linked to the infrastructure costs. There is a lack of analytic approaches transferring vehicle and infrastructure input to damage or wear on both sides. While in closed networks (especially in heavy-haul railway operation), vehicle and track are seen as two components of a combined system, this is not the case in open-access networks. As long as infrastructure parameters vary from IM to IM, it is unthinkable to proceed in optimal matching, as trains might run on several networks from the starting point to the destination.

This topic is considered once more in chapter 0.

2.2.6 Unit Costs

One major cost impact is derived from the unit costs for the various works. While labour costs naturally differ from country to country throughout the European Union, material costs are fairly equal, as they are influenced by global aspects. Although different track work machinery exists, machinery technology also seems to be equal.

The unit costs are influenced by the worksite output. This is true for all works and for all countries. The general rule of economy of scale determines that high outputs lead to low costs per output. Figure 33 shows this for UK worksites (red dots) and other European worksites.

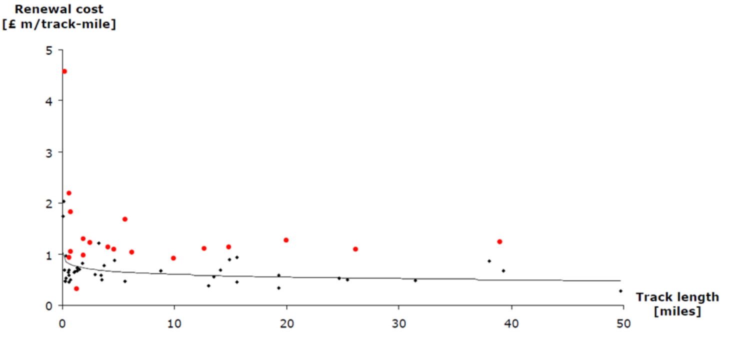

Figure 33 Track Renewal Cost as a Function of the Worksite Length [24]

In the railway sector, short sections are executed not only for technical reasons, but also due to the short availability of track closures for maintenance and renewal work. Track work, at least heavy maintenance and renewals, must be executed on closed tracks. However, a track closure disrupts or delays traffic and is therefore undesirable.

A balance between track work unit costs and operational hindrances can only be achieved by using the same unit – euros. It is necessary to quantify the operational consequences of a track closure as a first step: minutes of delay, and – for longer closures – bus services for passenger trains, additional train kilometres and delay minutes due to rerouting of freight trains, and the number of trains not operated. These consequences vary with the number of trains operated on a line, and with the period analysed. Depending on the line and the traffic mix, track closures in the night or at weekends lead to far fewer operational consequences than those during working hours.

Having achieved this by analysing the alternative timetable, these difference consequences must be quantified in euros. As e.g. delay minutes do not count equally for all train services, this must be carried out at the level of market segments. The costs of operational hindrances (COH) can be calculated using variable and fixed cost elements. Of course, the cost input data for the calculation must come from the RUs. The Austrian IM, ÖBB, has already been using a model like this since the 1990s. Other IMs have similar calculation schemes, sometimes using other cost inputs or fixed values for delay minutes.

ÖBB results show that for track renewal works, the savings in unit costs due to reinvesting longer sections override the increasing COH by far. Figure 34 provides an example for one transport load. In the case depicted, weekend work would increase costs. This means that the additional labour and machinery costs are higher than the saved COH.

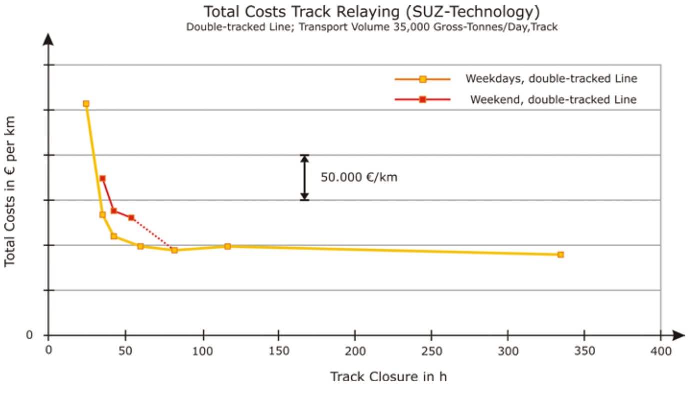

Figure 34 Total Track Renewal Cost as a Function of Track Closure Time – Medium-loaded Line [26]

Although results change from line to line and from track work to track work, a general conclusion was made in Austria: Existing track closure times are generally too short. This cannot be justified by follow-up costs at the RUs.

This is an area for system optimisation. As this topic influences the direct costs, it should be in the RUs' interest to contribute to the possible cost reductions. While the direct cost allocation is not affected by this topic, it could be used to define different slot qualities. Delay-sensitive trains that do not allow for sufficient track closure time could be charged at higher prices. This is discussed in detail in chapter 6.2.

2.2.7 Infrastructure's Quality Level

Everything concerning costs up to this point has been based on the general assumption that the quality level of the infrastructure is unchanged. At the end of the service life, in particular, the cost increase caused by heavy maintenance can be avoided by reducing the level of quality. If quality can no longer be guaranteed, speed restrictions must be imposed. A certain number of such slow orders is acceptable as long as time reserves in timetables are large enough to prevent train delays. An increasing and/or high number of permanent slow orders is a notable sign of either underfinanced maintenance and renewal budgets or an unsustainable maintenance regime.

If only the costs are considered, speed restrictions are a cheap measure to prolong service life or to shift maintenance action backwards. The IM can save a lot of money by doing less but setting speed limits. That should not be the goal in order to guarantee high performance of the system, of course.

This non-favoured strategy can be calculated at the cost level using the methodology described above. Speed restrictions lead to delays, and delays cause additional costs to the RUs.

2.2.8 Summary

All these cost drivers influence the direct costs. As most of these aspects are not technical aspects but rather strategic ones, there is no way to consider them in track access charges. Nevertheless, most of the effects discussed are known as qualitative correlations, but are not quantified. Only a cost assessment for every single asset type can indicate the quantitative input of the cost drivers to the direct costs. This assessment is a precondition for a possible consideration of a certain cost driver in the cost allocation. Some effects could be ignored, and it may be important to incorporate others for other reasons, but some of these aspects should definitely be subject to the cost allocation and should therefore be included in the track access charging.

2.3 Cost Assessment – the Standard Element Approach

It is necessary to describe infrastructure costs as a consequence of maintenance and renewal actions. The IM must have a sound basis for internal decision-making. Life-cycle cost analyses are state of the art, but data sources are often missing. The Standard Element (StdE) approach was first set up in Austria in a cooperation between TU Graz and ÖBB. This approach has also been used in Croatia (HZ), Switzerland (SBB), and is being set up in Sweden (TVK). Other IMs use similar approaches.

The goal of one StdE is to describe maintenance and service life for a certain set of boundary conditions. The main cost drivers (parameters) are combined in a fixed parameter set. For this parameter set, a working cycle consisting of all the relevant maintenance actions over the entire service life is generated. The input data is partly from data warehouses at the different IMs, from expert knowledge and field experience.

Even though the topic is well published [27][28][29][30], the main ideas of this approach are described briefly in this chapter, as this approach is important for the cost analyses (chapter 2.4) and the cost allocation (chapter 0).

The working cycle depicts the maintenance actions over the entire service life. It is important to note that the maintenance demand and service life itself are average values. Either the deviations from the average come from parameters that are not included or from different general strategies (see especially chapters 2.1 and 2.2.3) applied in different regions within the network of one IM.

Figure 35 provides an example of a working cycle. The analysed asset is a high-loaded, double-tracked section in a curve (radius between 400 and 600 metres). On good subsoil, a heavy superstructure consisting of 60E1 rails with a steel grade of R350HT and concrete sleepers equipped with soft pads (USP = Under Sleeper Pads). For this track with about 25 million gross-tonnes yearly, the optimal service life is 29 years under the assumed maintenance regime (calculation according to Figure 25).

Line A	400<R<600	double-tracked															
Gross-Tonnes/Day,Track	Rail Profile	Steel Grade	Subsoil		Sleeper Type												
high-loaded	60E1	350HT	good		concrete USP												
Track Work	SL in years	29,0	0	1	2	3	4	5	15	16	17	23	24	25	26	27	28
Renewal		1,0	1														
Tamping	every x years	4,1	1				1			1			1			1	
Rail Grinding	amount in SL	5,0					1			1			1			1	
Rail Exchange	amount in SL	0,6								0,3							
Joint Maintenance	amount in SL	0,0															
Rail Pad Exchange	amount in SL	0,0															
Small Maintenance	amount in SL	29,0	0,5	0,5	0,5	0,5	0,5	0,5	1	1	1	1,5	1,5	1,5	1,5	1,5	1,5

Figure 35 StdE Working Cycle – Example

Maintenance actions have different values in the working cycles. “1” indicates e.g. rail grinding of the whole section. “0.3” indicates either rail exchange in 30% of the section or in 30% of all sections forming the average. The values in the last row must be viewed differently. Small maintenance is covered by a superstructure-, subsoil- and transport load-dependent average yearly amount of money. The value “0.5” indicates that half of this average amount is spent (first third of the service life), and “1.5” stands for 50% higher expenses than the average per year (last third of the service life). This was introduced to reflect increasing demand for spot repairs when assets grow older.

ÖBB set up around 500 standard elements for tracks, always changing one of the parameters in the first three lines in Figure 35. Approx. 50 of those are able to describe about 90% of the entire network. In addition, the subsoil quality was changed for some of the most relevant parameter sets. Standard Elements exist at ÖBB for track [31][32], turnouts [33][34] (including different turnout heating systems [35] and different setting and locking types [36]), catenary [37][38], bridges [39], level crossings [40], platforms [41], and noise barriers [42]. At the SBB [43] and in Croatia [44][45], standard elements for tracks and turnouts have been worked out.

Standard elements are helpful tools for different tasks:

- Maintenance and Renewal Demand
  If standard elements are merged with the real network, average yearly maintenance and renewal demands can be derived. Maintenance demand is thereby specific to a single maintenance job (e.g. x km of overhead-wire exchange). By combining this information with average unit costs, network-wide budgets can be estimated. Note: Standard elements deliver average values. Maintenance planning is not possible with average behaviour, but must be based on the actual condition.
- LCC-based Decision-making
  Based on the costs that can be calculated by multiplying the amount of work in the working cycles with unit costs (total LCC), decision-making for general strategies as well as for component strategies can be supported. As costs of operational hindrances are an integral part of the unit costs, the costs of non-availability are included.

These standard elements form the basis for the following cost analyses. All the figures are based on a sustainable, LCC-optimised situation if not marked otherwise. The analyses provide average annual costs per asset type (and unit). Economic analyses are executed dynamically, including a general interest rate of 5% net for new technology. The annual costs depicted are calculated statically (interest rate 0%). Red bars always signify total costs (LCC as average annual cost). Green bars show the depreciation (reinvestment costs divided by the economic service life, while yellow ones show the average maintenance expenditure per year. Blue bars (if shown) are costs of operational hindrances. Figure 36 provides an example, covering topics discussed above.

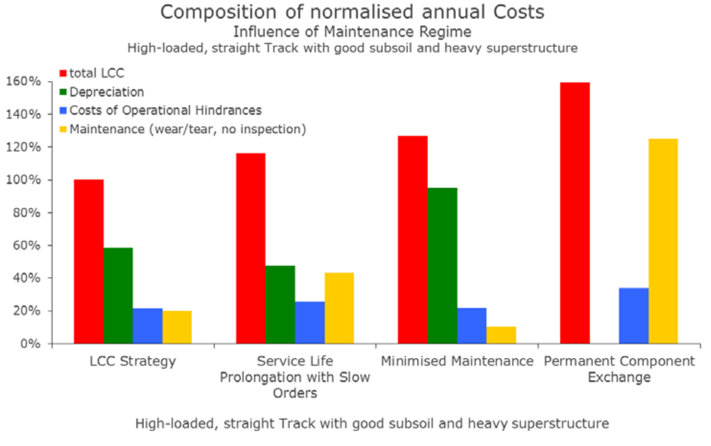

Figure 36 Cost Analyses – Maintenance Regime

2.4 Cost Analyses

2.4.1 Track

Track is the costliest asset type. Additionally, the maintenance costs of track must be considered to a very high degree in the direct costs, due to the implementing act. The following analyses for track only include wear-dependent maintenance; inspection is not considered.

The Influence of Transport Volume

Track loading is internationally depicted by gross-tonnage for tracks. The influence of different vehicles in the total train collective is not covered by the analyses shown. This topic is addressed below, in the cost allocation chapter (chapter 0).

Figure 37 shows the cost increase with increasing transport volume.

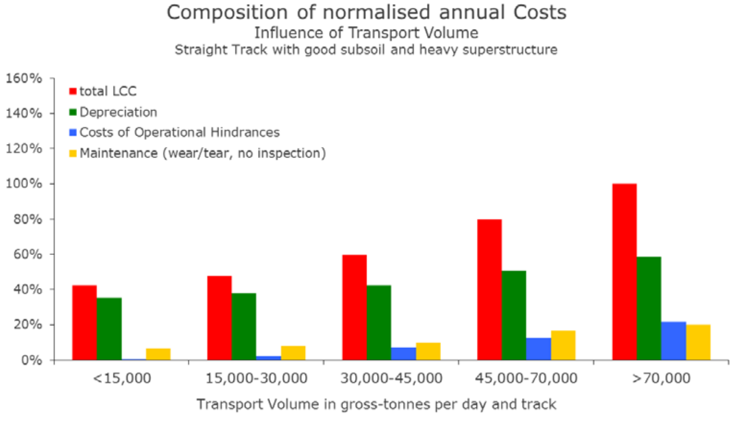

Figure 37 Track Costs – Transport Volume

Maintenance (yellow bar) is increasing almost linearly. This indicates that the maintenance considered is doubtlessly "cost that is directly incurred" by a train run. It is only for low-loaded tracks that parts of the maintenance are obviously time-dependent.

Another aspect is the depreciation. As depreciation increases with growing transport load due to a decreasing service life, parts of the reinvestment costs are wear-dependent and must therefore be considered in the direct costs.

The Influence of Track Radius

Curved track results in higher maintenance expenditure of a different kind. If track radius decreases, the maintenance actions for the rails increase dramatically and track geometry corrections are much more frequent. In very narrow curves, the costs of changing the outer rails due to railhead side wear dominate the overall maintenance costs. X shows this effect, which leads to maintenance costs that are 16 times higher for jointed tracks in radii smaller than 250 metres compared to tangent tracks. Moreover, the maintenance costs originate from very different wear processes. In curved track, rail maintenance is much higher, due to rail contact fatigue on the surface and rail wear on the outer rail. Maintenance on curved track can be reduced by using higher steel grades for the rails and optimised track systems consisting of modified rail pads, rail fastenings, and elastic footings for concrete sleepers, or an innovative sleeper design like HD sleepers or frame sleepers. In any case, the lower maintenance is paid for with higher (re)investment costs.

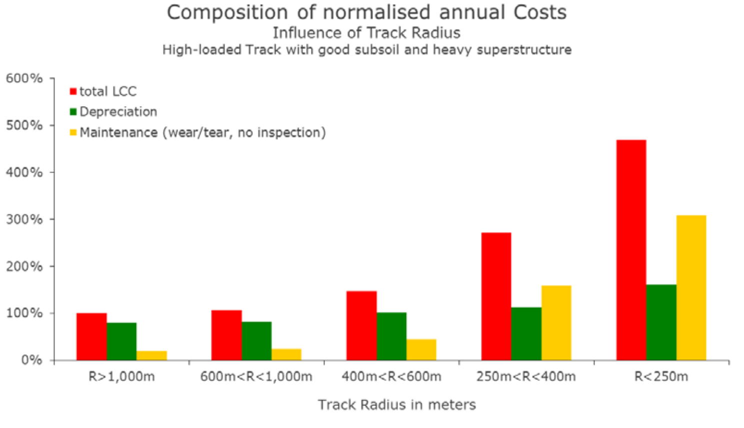

Figure 38 Track Costs – Track Radius

It is important to note that in smaller radii, the maintenance costs are higher than depreciation. Again, depreciation is not constant as service life decreases with decreasing radius. In this case, there is also a certain amount of wear-bound reinvestment costs.

In order to extract more information about maintenance costs, the yellow bars are analysed in detail. The increase of rail maintenance can be seen clearly. Changing the rail steel grade from standard grade R260 to R350HT helps to reduce wear and consequently lowers the rail exchange expenditure. In addition, rail-grinding costs are reduced, beginning in radii under 1,000 metres. The comparably low savings in average yearly maintenance are sufficient to justify economically the additional material costs of R350HT rails in renewal.

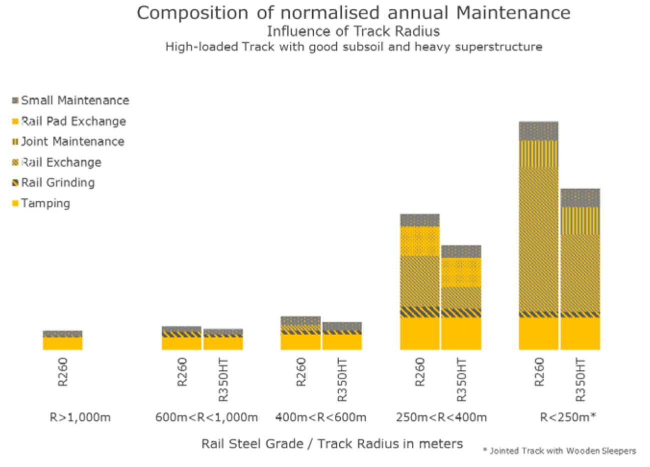

Figure 39 Track Maintenance Costs – Track Radius

This evaluation is a strong hint that track radius should be a parameter in the modulation of direct costs. Track radius is listed in the Implementing Regulation for good reason.

<u>The Influence of Superstructure and Substructure</u>

For many infrastructure managers, the costs for re-establishing proper track geometry (tamping, ballast cleaning) are one of the highest cost proportions in track maintenance [46]. In addition to the ballast quality, the substructure is decisive for maintenance costs and the service life of track. As Figure 40 shows, track maintenance increases to a level seven times higher if the quality of the substructure is poor. Improvement is costly and only economically feasible with reinvestment of the track superstructure.

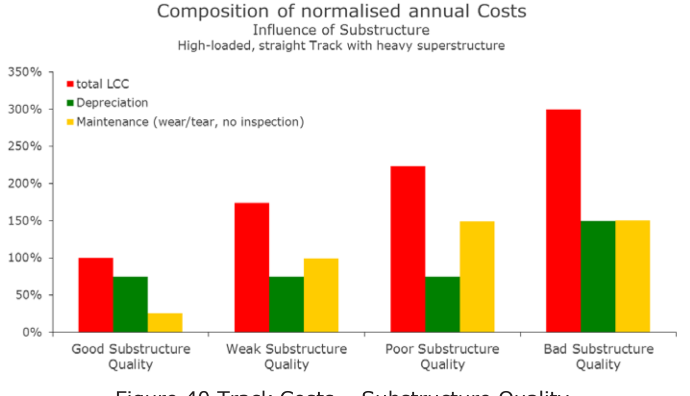

Figure 40 Track Costs – Substructure Quality

Different types of superstructure also lead to changes in track maintenance costs. For high-loaded tracks, differences between slab track and light superstructure ballasted track range up to a factor of 7. Figure 41 depicts average annual costs of superstructure, but does not cover possible additional substructure costs for slab track.

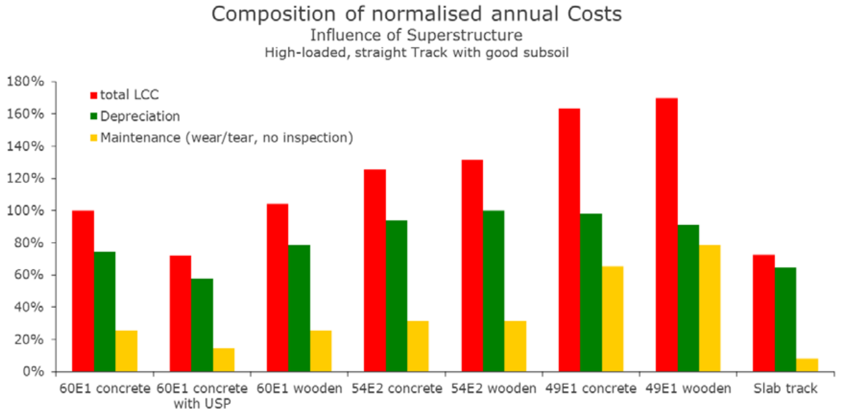

Figure 41 Track Costs – Superstructure

These evaluations are more important for track optimisation than for track access charging, as older superstructures are normally replaced in standard reinvestment procedure with newer (low-maintenance) ones. In an entire network, lines show older and newer tracks as mentioned above, so that different superstructures (and different track ages) occur in a certain mix. In any case, tracks with under sleeper pads show significantly lower maintenance costs due to less deterioration in quality (Figure 42).

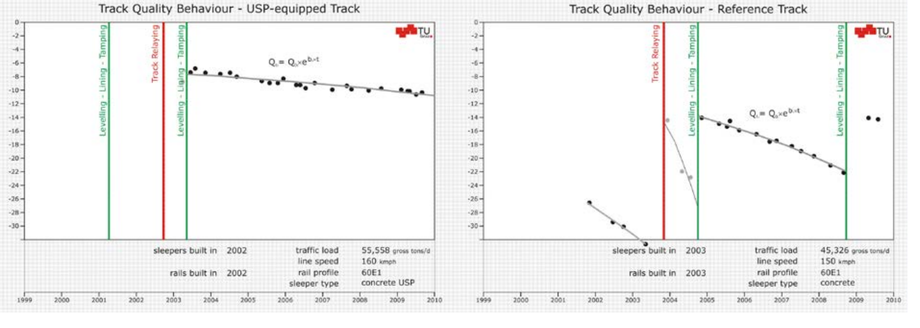

Figure 42 Track Quality Behaviour – USP Tracks

The same is true for slab tracks. If these two superstructure types are in use, costs are much lower. This is particularly the case when it comes to new lines.

The Influence of Speed

Higher speed levels demand stricter intervention limits for track geometry. These stricter limits lead to more frequent tamping actions and thus higher tamping costs. This effect is not depicted in the general data set of the standard elements in Austria and Switzerland. In Austria, the influence of increasing speeds was analysed for one case. The case shown is valid for an increase of speed from 160 km/h to more than 200 km/h (Figure 43).

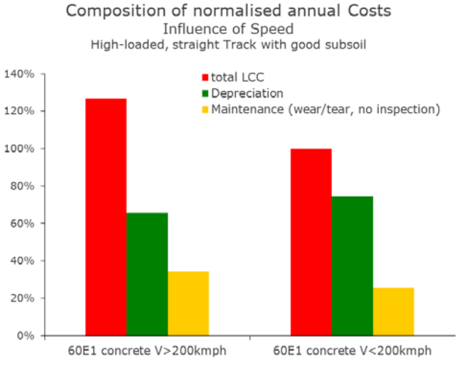

Figure 43 Track Costs – Speed

A more detailed view on the influence of speed on maintenance costs of track is provided in chapters 3.1.1.5.4 and 3.1.4.1.

The Influence of Turnouts

Turnouts are expensive assets. Component complexity, moveable parts, and partly undefined wheel-rail contact are reasons for the high cost level. Recalculated to one metre of through-going track, costs of maintenance and depreciation exceed track costs by 7 times (LCC). In addition, the relation between depreciation and maintenance costs is different in turnouts: They are almost equal. In terms of the maintenance costs, this means that the cost level per m of through-going track is 13 times higher.

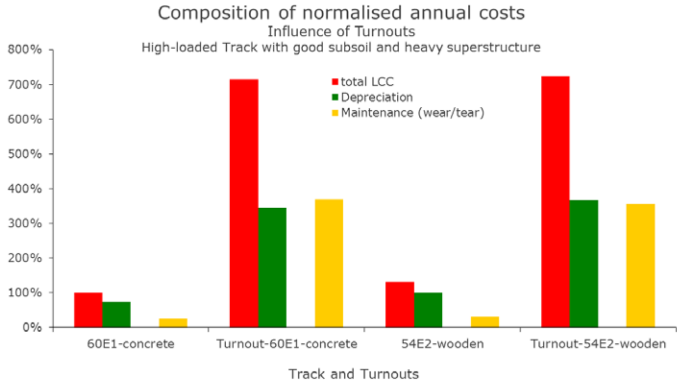

Figure 44 Track Costs – Turnouts

Dealing with these high costs of point infrastructure is a challenge – in day-to-day asset management as well as in cost allocation. Turnouts in curves lead to even higher maintenance cost (Figure 45).

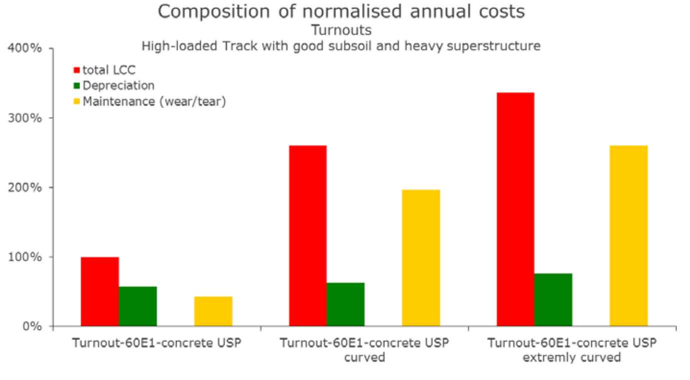

Figure 45 Turnout Costs

Summary

It can be shown that track costs vary widely due to numerous influencing parameters. While some parameters are easy to identify, for example track radius or turnout frequency, others can only be addressed with detailed asset data available (e.g. superstructure). One parameter, unfortunately with a high cost impact, is not covered by network-wide statistics as is difficult to obtain: the subsoil quality. A major aspect in today's track asset management is to overcome this lack of knowledge.

Cost impacts of parameters differ and change rapidly with changing parameter values. It seems that the cost impact of transport volume is easy to describe – it is linear (or at least almost linear). This enables a very rough estimation of cost levels. Whenever other parameters influence this effect, which is often the case, the linear influence of transport volume is prevented. If transport volume is the only parameter considered in cost allocation, high deviations must occur. Figure 46 shows results for different line properties with one parameter unchanged: the transport volume.

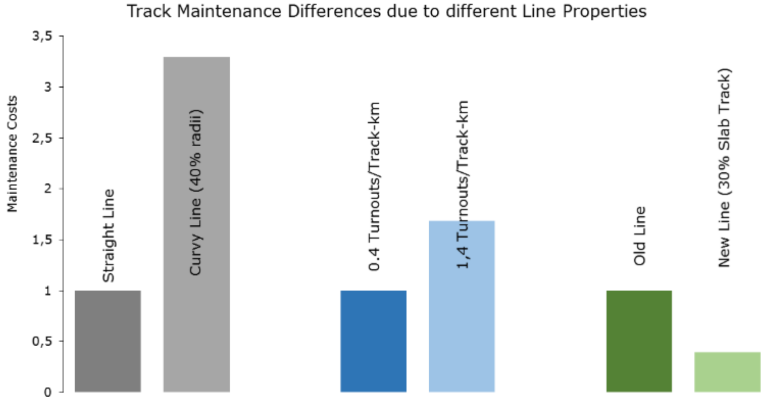

Figure 46 Track Costs – Different Line Properties

Vehicle characteristics have an impact on the track costs, of course. Due to a lack of data and the fact that integral track deterioration models (TDMs) are unavailable or rarely validated, cost analyses are missing. Chapter 3.1.1.5 presents models like this. The future will show if these models succeed in being used in track asset management when data availability changes.

2.4.2 Catenary

Based on standard elements, similar evaluations are possible for catenary. Figure 47 shows clearly that only the costs of overhead wire are wear-related for the asset catenary. This is true for reinvestment as well. These costs are also indicated in Regulation 2015/909 [18].

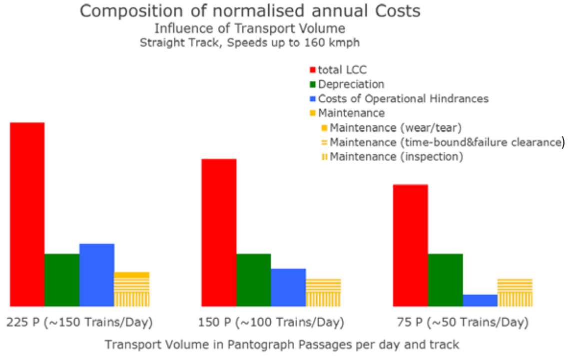

Figure 47 Catenary Costs – Transport Volume

<u>The Influence of Track Radius</u>

Catenaries are more expensive in the case of smaller radii. In reinvestment, this is because the masts have to be built at shorter distances. Figure 48 indicates this, since depreciation is higher at equal service lives. Additionally, maintenance costs are higher. This is not due to more maintenance but rather to higher unit costs as a result of unfavourable boundary conditions (in the smallest radius, 30% higher). This effect could be considered in the direct costs, although the cost differences are small in terms of absolute values.

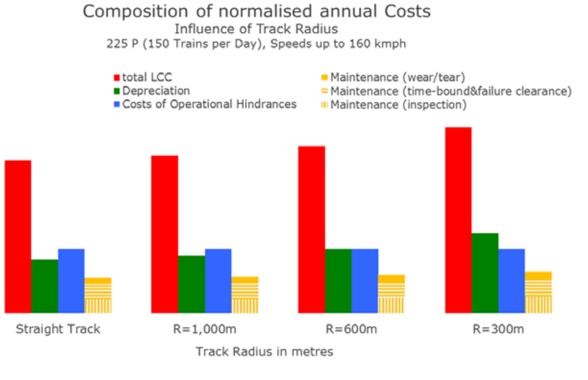

Figure 48 Catenary Costs – Track Radius

The Influence of Speed

If speed levels are increasing, different catenary systems are installed. These systems have the same service lives and equal maintenance frequencies. Unit costs are higher due to higher material costs and higher system complexity. This is especially true for speeds higher than 160 km/h.

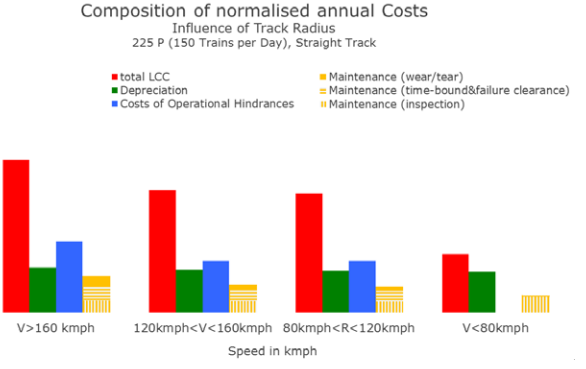

Figure 49 Catenary Costs – Speed

2.4.3 Bridges

In an analysis of the costs of bridges, it becomes apparent that the costs are very different for different types of bridges (Figure 50). However, maintenance is overwhelmingly time-bound. The costs of bridges are therefore not analysed in detail.

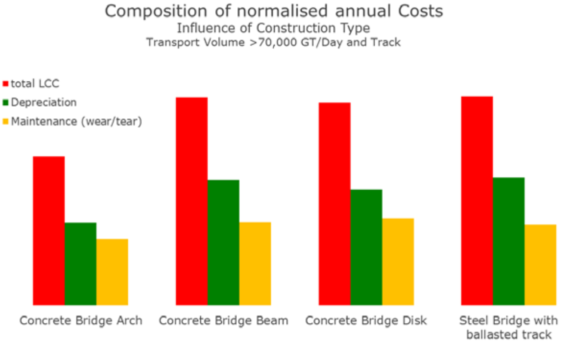

Figure 50 Bridge Costs – Construction Type

Note: Load-dependent maintenance might occur if bridges are overaged. For some IMs in Europe (UK, CEE countries), bridge costs might therefore be relevant in terms of direct costs. In the case of the UK, Network Rail calculates with 5% and 4% of the renewal expenses of metallic underbridges and brick and masonry underbridges. [47]

2.4.4 Tunnels

Tunnels are high-maintenance assets. This is not due to the track (slab track is very common for tunnels, as subsoil conditions are perfect), but rather to time-bound maintenance such as drainage cleaning. Tunnels do not therefore contribute to the direct costs.

2.4.5 Signalling

Signalling equipment does not generally need to be considered in the direct costs according to Regulation 2015/909 ([18] Article 4 (h)). For signalling assets in turnouts, there may be a low correlation between transport load and maintenance and renewal costs. In the UK, these costs are estimated to be variable at around 5% [47]. Compared to the direct costs of track, this is a minor cost position.

2.5 Summary

Asset costs vary widely. Even for the same asset types, notable differences occur due to different effects. These technical aspects should be considered in the direct cost calculation in as much detail as possible.

Generally, the asset types, qualities, maintenance philosophies, and existing budgets differ strongly throughout Europe. This influences the absolute height of the direct costs. In any case, only sustainable infrastructure budgets can ensure that asset cost analyses or data from cost accounting systems deliver long-term stable direct costs. While the cost height differs, the technical system behaviour does not. This situation has little impact in the following cost allocation approaches: Cost calibration factors must be calculated separately for every network due to different heights of the direct costs.

Detailed cost accounting systems or the standard element approach (or similar approaches) can deliver detailed maintenance costs. These costs are broken down to single maintenance actions and track sections. This is a necessary precondition for any detailed cost allocation.

Assuring this precondition is not the easiest task for an IM. How does an IM generate this data if maintenance is outsourced based on lump sums, and contractors are not willing to share their knowledge and data? Once again, this is a topic of proper interfaces. In addition to all the financial aspects, the asset data in terms of technical behaviour and the resulting maintenance costs must always be available to the IM. This has to be assured by contracts.

On general aspect must be highlighted: The IM's aim should be to generate the lowest possible total costs for every asset. This means an optimisation of the LCC, of course. All evaluations show that low LCC are only on high quality levels. This does not result in the lowest maintenance costs. Any technological improvement is paid at the point of reinvestment and is therefore not included in the direct costs. Involved long-term maintenance costs are, however, lower. This means that in a sustainable, high-quality network, direct costs must be lower than in an overaged, poor quality one.

3

Cost Allocation

In order to support the cost allocation process with figures, a simplified network is used, which is described in the Annex. The iTAC network consists of mixed traffic, lines with high transport volumes as well as lower ones, and tracks with speeds of up to 200 km/h and down to 60 km/h (detailed speed levels per line segment covered). It covers around 1,000 kilometres of track. Information on track superstructure and track radius, track age and turnouts (superstructure, size, alignment) exists. Transport volume is given in gross-tonne-kilometres and train-kilometres for a period of six years. The composition of trains (vehicles) and the loading of freight wagons is estimated on the basis of the existing data. Only anonymised vehicle data is used, although this data is real.

The cost allocation in this chapter is a line-specific approach. Average network values are always calculated additionally where possible. All the evaluations presented are based on real costs. Results are given without any cost figures. This is due to confidential data, on the one hand, but also due to the fact that the values only fit for the network analysed. Any comparison to existing networks would lead to the wrong conclusions. This is indicated separately in the following chapters.

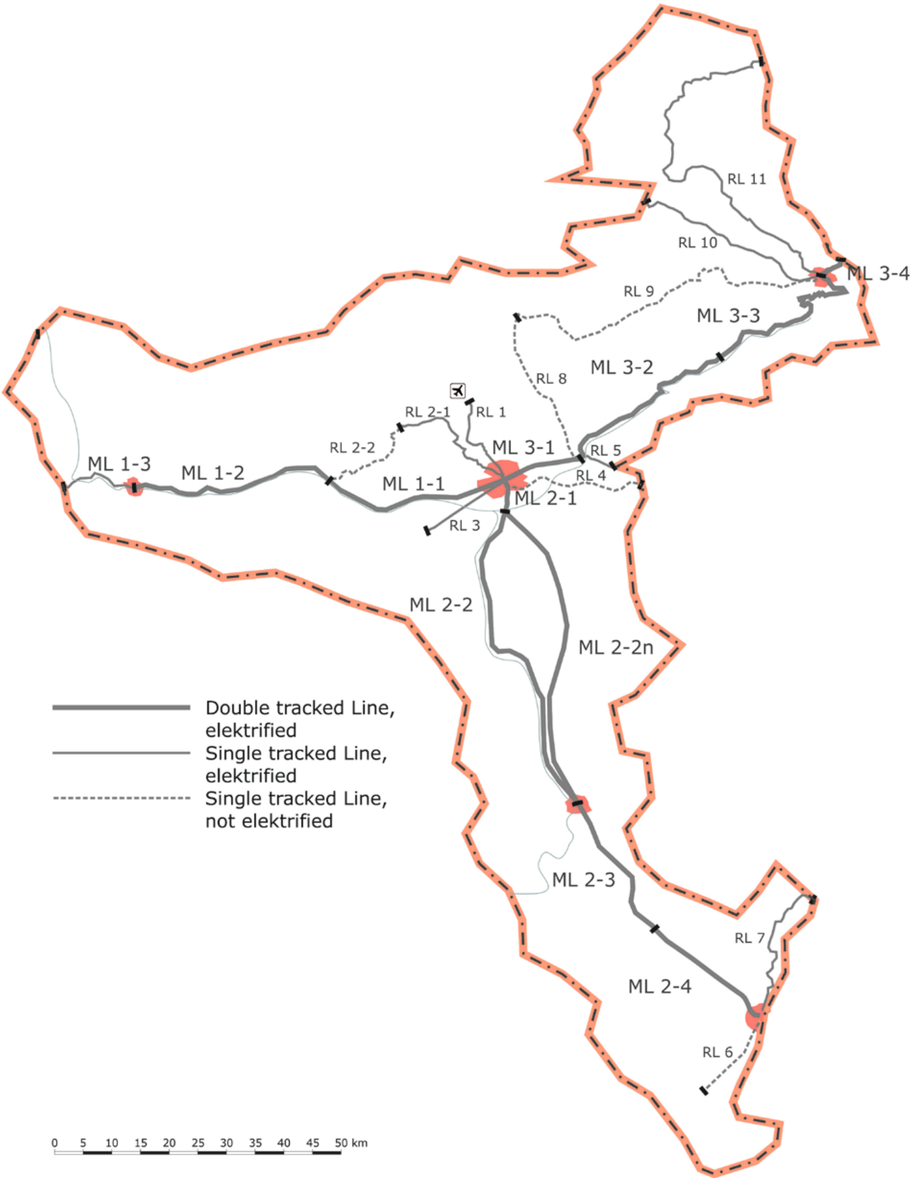

Figure 51 The iTAC Network

3.1 Marginal Cost of Track

3.1.1 Maintenance Costs

3.1.1.1 Evaluation of the Marginal Cost Level – Maintenance

By far the simplest way to calculate the track wear and tear costs due to a train run is defined in Implementing Regulation 2015/909 [18]: Taking the network-wide costs from the cost accounting and dividing it by the number of train-kilometres or gross-tonne-kilometres. For track, it has already been shown that the gross-tonnage and not the number of trains is the influencing parameter for the maintenance expenditure. A simple cost/unit calculation based on the cost accounting data does not indicate this. In both cases, track maintenance cost divided by train-kilometres (Figure 52) or by gross-tonne-kilometres (Figure 53), deviations from the net-wide mean value are very high.

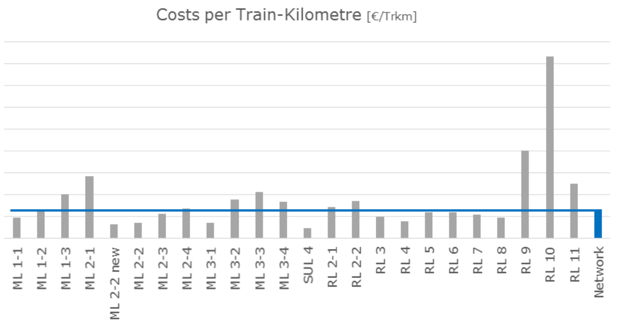

Figure 52 Average Track Maintenance Costs per Train-Kilometre

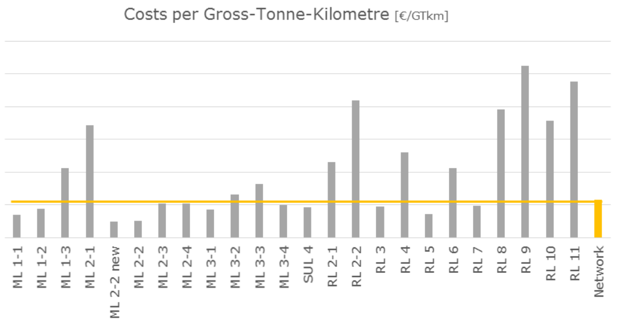

Figure 53 Average Track Maintenance Costs per Gross-Tonne-Kilometre

Nevertheless, these are average costs and not marginal ones. Furthermore, it is essential to explain the deviations, as the goal is to calculate costs directly incurred by operating a train service.

When the lines are rearranged by the number of gross-tonnes per track and day, the picture changes slightly (Figure 54): high-loaded tracks tend to have to a stable value (ML 2-2, 2-2 new, and 2-1 still show significant deviations), while low-loaded tracks face much higher costs per gross-tonne-kilometre and show much higher deviations.

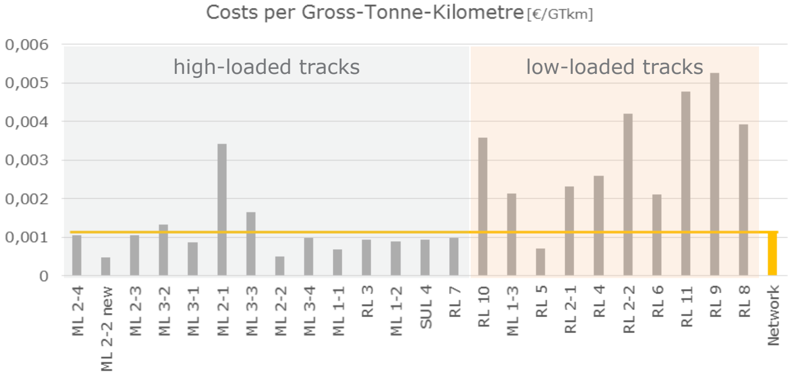

Figure 54 Average Track Maintenance Costs per Gross-Tonne-Kilometre

Plotting this result on unit cost to gross-tonnage scaling shows the effect more clearly:

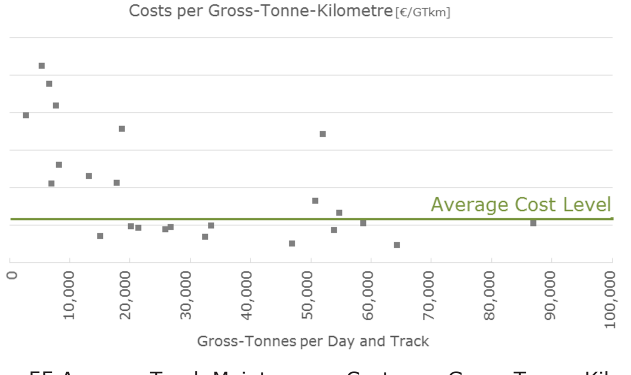

Figure 55 Average Track Maintenance Costs per Gross-Tonne-Kilometre

Figure 55 indicates that marginal costs, or rather the costs of wear and tear, increase with decreasing transport volume, whereas they level out in a logarithmic way towards higher loaded tracks to a certain value. This does not result in anything new. This result is already calculated and documented with a higher number of track sections by various authors. Economic and engineering models show that the marginal costs on low-loaded lines are higher. [48][49]

From an engineering point of view, there could be two possible reasons for this:

- On low-loaded tracks, specific maintenance works are not carried out due to the impact of loads, but rather to keep the system running. One example is track tamping, where track experts recognise the necessity of tamping the ballast after a certain period of time to ensure elasticity of the ballast bed. This is therefore carried out due to a time period that has passed, rather than due to loading. In this case, the maintenance is time-bound and not connected to wear and tear. This means excluding such maintenance costs from the evaluation of marginal costs, as they are not linked to a train run.
- On low-loaded lines, it is very likely that the IM chooses a different maintenance regime. Track renewal in order to guarantee the lowest LCC requires financial funds over a long period of time. On low-loaded track, this time is significantly longer than on track with high tonnage (see Chapter 2.1). If future train operation is questionable due to low market potential, it is economically justifiable to increase maintenance costs and to skip the LCC-based economic optimum. If lines are closed where renewal work has been carried out, the loss is much higher.

In reality, both cases occur. Very detailed knowledge and data are necessary to prove the second case, and that is not the focus of this work. For the purpose of track access charging, it is irrelevant whether one of the other cases is true. The RUs should be charged for the lowest marginal costs (strategic costs), so that even higher wear and tear costs (second case) are not included in the charge, as they are the result of an economic decision made by the track owner/investor. Track investment (the part of it not related to wear and tear) is not within the scope of Implementing Regulation 2015/909 [18].

This leads to a major definition for all further evaluations in order to determine proper TACs:

Principle I: Marginal Cost-based Charging

The costs evaluated are set to the level of wear and tear costs of high-loaded tracks. In the case of higher costs on low-loaded lines, residual costs will occur, which are defined as costs that are part of "providing the infrastructure" (similar to the costs of inspection and fault clearance). This definition prevents costs being shifted from low-loaded lines to higher loaded ones.

To evaluate this in more detail, the low-loaded lines must be separated from the calculation. From the data used, the minimum transport level is set to 20,000 gross-tonnes per day and track or around 7 million gross-tonnes per year. In contrast to Figure 55, Figure 56 has a low cost level (yellow), named "Marginal Cost Level".

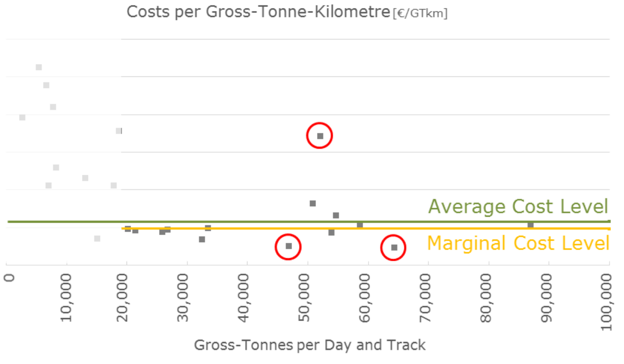

Figure 56 Marginal Track Maintenance Costs per Gross-Tonne-Kilometre

The three outliers marked with red circles show significantly deviating values: two lower ones (about half of the marginal cost level) and one much higher one. These three lines are excluded at first, as they have extraordinary infrastructure properties. These lines are added again later on. As the two lines with the low unit costs add a lot of gross-tonne-kilometres due to their length, the marginal cost level increases until it is only slightly below the average (Figure 57).

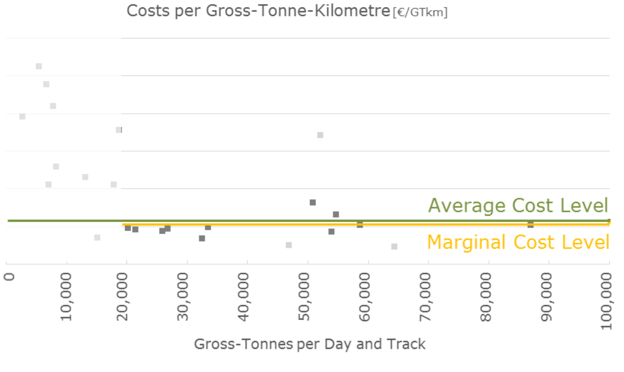

Figure 57 Marginal Track Maintenance Costs per Gross-Tonne-Kilometre II

The marginal cost level has been defined by using the gross-tonne-kilometre as the cost unit. This was a first estimation, as the international track community also uses this unit for its analyses. The evaluation above is based on 11 line segments. These line segments with their averaged maintenance cost (over six years) form the basis; reference is made to all the following evaluations. The indicator for the model accuracy is the cost recovery on every line segment, as the total amount of money is the same for all approaches.

The evaluation network covers 535 km of track carrying almost 8.8 billion of gross-tonne-kilometres per year, 21% long-distance passenger trains (LDP), 15% regional passenger trains (RP), and 64% freight trains (F). The lines are long-distance, regional and suburban, and they cover straight lines, high-speed lines and mountainous, curvy lines. The yearly track maintenance costs total around 10 million euros.

As the lines have different lengths, number of tracks and turnouts, and transport volumes, the total track maintenance costs are significantly different (Figure 58).

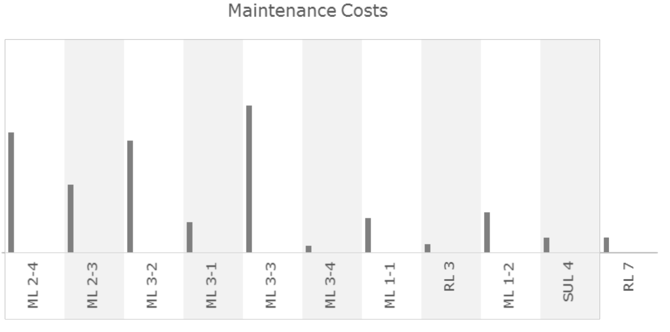

Figure 58 Maintenance Costs on the Evaluation Lines

3.1.1.2 The Gross-Tonne-Kilometre Approach

This approach repeats the evaluation described above. As it is assumed that the costs covered are marginal costs, the total sum is divided by the total number of gross-tonne-kilometres. The total gross-tonne-kilometre charge calculated is then redistributed to the line segments by the number of gross-tonne-kilometres on the lines.

The accuracy of this approach is depicted in Figure 59: For some lines, the fit is quite acceptable, whereas for others, the deviation to the actual cost is high. Seen as a gross-tonne-kilometre weighted average, the total deviation of this approach is plus/minus 21%.

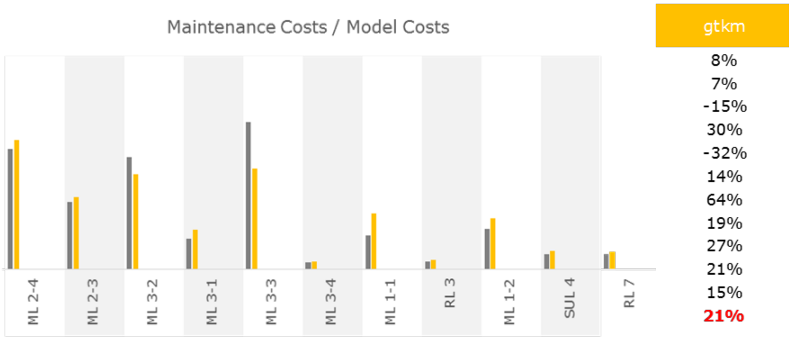

Figure 59 Accuracy of the Gross-Tonne-Kilometre Approach

This is not particularly surprising. The approach covers the loading of track as the only parameter from all those mentioned in chapter 2.4.1. To provide more realistic results, the transport load needs to be described in more detail. A modified gross-tonne definition would help. Such a definition can be found in the UIC 714 Code on the classification of lines for the purpose of track maintenance. [50]

3.1.1.3 The UIC 714 Fictive Gross-Tonne-Kilometre Approach

As Calco et.al. [51] propose, the use of the theoretical traffic load following UIC Code 714 [50]in charging schemes would increase the accuracy of the gross-tonne-kilometre approach, since the main indicators that harm track (weight, speed, axle load) are covered. Since this is an average approach, specific axle loads are not actually covered. When the formula (EQ 3) is analysed, only powered axles of locomotives and axles of freight vehicles are treated as "more harmful" to track. A similar formula is used in the Railway Group Standard 5023. [52]

$$T_f=S_v\times(T_v+K_t\times T_{tv})+S_m\times(K_m\times T_m+K_t\times T_{tm}) \quad \text{EQ 3}$$

with

T_f	Theoretical traffic load
T_v	Tonnage passenger traffic non-powered
T_{tv}	Tonnage passenger traffic powered
T_m	Tonnage freight traffic non-powered
T_{tm}	Tonnage freight traffic powered
S_v	Coefficient "speed" passenger traffic (ranging from 1.00 for speeds below 60 km/h to 1.40 for more than 160 km/h)
S_m	Coefficient "speed" freight traffic (equivalent to S_v but not defined above 130 km/h)
Kt	Coefficient "aggressiveness" of powered axles, Kt = 1.40
K_m	Coefficient "aggressiveness" of freight axles K_m = 1.15 is used, as the percentage of 20.0/22.5to axles is not higher than 50% for freight traffic in mixed traffic networks

In order to apply this approach, it is necessary to know more about the trains running on the network than their total weight. Depending on whether this additional information is created by very general assumptions (average train weights, assumed powered axles, average speed levels, etc.) or is obtained from more detailed information on speed profiles, radii distribution, and train compositions, the result may be more or less accurate.

Figure 60 shows that the approach is less accurate than the simple gross-tonne-kilometre approach for the network analysed.

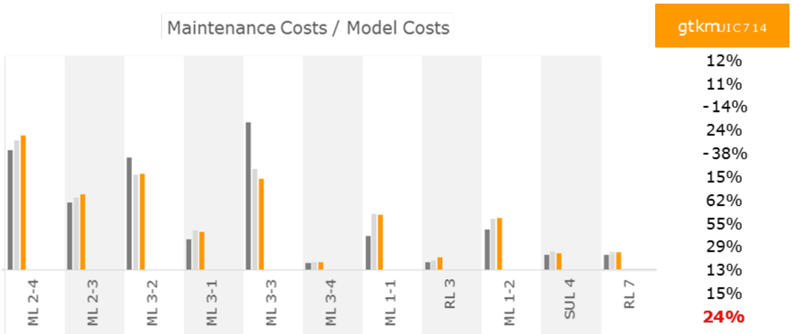

Figure 60 Accuracy of the UIC 714 Fictive Gross-Tonne-Kilometre Approach

This can be explained quite easily with knowledge of some infrastructure details of the lines analysed: In the case of ML 3-3, where the gross-tonne-kilometre approach produced a cost level that was far too low, it becomes apparent that the UIC 714 approach [50] allocates even fewer costs to this line. This line is a mountainous line consisting of a high radii percentage and naturally low speeds. While the maintenance costs are high (see chapter 2.4.1), the UIC 714 approach allocates even less damage to the line, as speed is lower than on the other lines.

Note: A precondition for being able to calculate this approach properly is the availability of data on

- speed level, section-wise on the line segments, and
- trains (powered axles/non-powered axles).

In summary, it is possible that this approach fits for networks and/or lines with almost no radii and homogenous infrastructure parameters on all lines. For a mixed traffic network like the iTAC network, it produces a poor result. According to Figure 60, it would be better to retain the gross-tonne-kilometre approach.

It becomes apparent that the infrastructure properties must be considered to a greater extent. This allows for a different approach based on the standard elements defined in chapter 2.3.

3.1.1.4 The Standard Element Approach

To return to the analysis from chapter 2.3: The track parameters define the costs to a very high degree. Some of these parameters can be covered without too much effort: Many IMs have data warehouses covering track radius and superstructure components, at least. Turnouts, their size and superstructure components are also often covered. Information on substructure conditions is not generally available. Track age also influences the maintenance level significantly but, as part of an initial approach, it can be assumed that new and old track balance each other out on a longer line segment.

As the basis of this approach, the line segments are “rebuilt” with standard elements. As standard elements cover strategic maintenance on an LCC-optimised level, it is necessary to shift the cost level to a slightly higher range. This is also necessary because information on inappropriate subsoil conditions is not available net-wide, so that standard elements used in this approach are defined as always having “good subsoil” (which is certainly not the case in every network).

The accuracy of this approach is shown in Figure 61. With a net-wide average deviation of plus/minus 20% to the real costs, the approach does not seem to be much better than the previous ones. What becomes apparent, however, is that this approach adds information, especially when it comes to radii (see ML 3-3). Lower loaded line segments are overestimated, while the high-loaded ones recover too little of the costs.

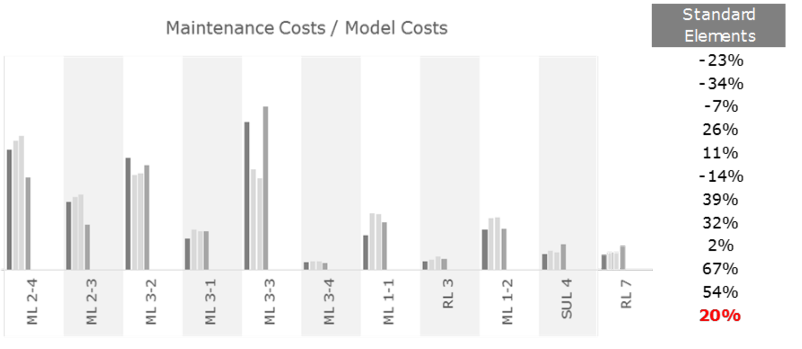

Figure 61 Accuracy of the Standard Element Approach

This result was foreseeable. The standards elements used do not consist of any speed description, but are set as an average approach covering speed ranges of up to 140/160 km/h. The cost unit is the gross-tonne-kilometre once more. The obvious, high influence of the track parameters and the turnout density lead to a second principle for proper track access charging:

Principle II: Line or Line Segment based Charging

The differences between the wear and tear costs of different line characteristics are much too high to be averaged. Line-based charges are necessary in order not to shift costs from high-cost lines to low-cost lines.

As the cost unit is still the train weight, the major wear and tear processes are not described properly. For a top-down approach, gross-tonne-kilometres might be sufficient, but the tonnage itself is only partly connected to the damage mechanisms. These are triggered by the axle load, the dynamic impact of unsprung wheel masses (and therefore the speed), the applied traction power, the lateral stiffness of the vehicle defined by the bogie concept, and the track radius. Top-down models are inappropriate to cover these vehicle properties. To connect vehicle properties and track parameters, a track deterioration model (TDM) is required.

3.1.1.5 TDM Approaches

Four TDMs are analysed, although not in great detail. One approach was elaborated in Switzerland at the SBB in recent years. This approach will be introduced into Switzerland's TAC model from 01.01.2017. The second approach analysed is similar and was set up in Sweden at KTH and Trafikverket. The third approach is the only one that is already part of a charging scheme, and is from the UK. All three approaches have similarities, but also notable differences, as shown below. The fourth approach is a hybrid model generated as a mix of a modified Swiss approach and the Swedish approach.

At this stage, it should be noted that TDMs describe damage mechanisms by different stress collectives instead of loading. The methodology to use these stress collectives for the cost allocation is the same as simply using gross-tonnes: The total amount of damage indication is calibrated with the maintenance costs necessary to re-establish a useable infrastructure. This process, the cost calibration, only redistributes costs. The total sum of costs is kept constant. The net-wide costs for e.g. tamping are divided by the vertical impact forces (this applies for all three models). It is therefore necessary to know the different cost proportions. The standard element approach (3.1.1.4) provides detailed costs like these. If such a basis does not exist, including net-wide, costs for different maintenance actions are feasible.

Additionally, it is necessary for the required vehicle data for the different models to be available. Depending on the models, this requires a mix of discrete calculations and simulations. These vehicle properties cannot be averaged or assumed. They must be available for all vehicles. For this paper, simplifications have been made: Trains have been assembled on the basis of given information and best knowledge. While all vehicles must be classified in implementation, this is not necessary for the purpose of proving models.

To be able to calculate/calibrate the models, the trains on the network must be detailed to vehicle-level. In addition to the information on infrastructure, its maintenance, and the vehicle properties, it is essential to know the operational conditions of the vehicles in terms of speed level on single track sections. The combination of track design, speed, and vehicle properties makes it possible to calculate the stresses due to every vehicle, and the total stress collective on a certain track segment.

The methodology described is a detailed, technical analysis and is therefore naturally much more complex and time-consuming than the approaches discussed above, but it comes quite close to the goal of extracting the costs directly incurred by a train run.

It should be underlined that a proper TDM is not only desirable for the purpose of access charging. Knowing the cause-wear-cost relation also enables the IM to establish a prognosis on future maintenance action and – on a larger scale – to estimate how maintenance and its total costs will develop in the future, especially when rolling stock mix changes and/or speeds are increased.

3.1.1.5.1 The Swiss TDM Approaches

The Swiss approach is a fairly detailed one, focussing on the four main cost drivers in track maintenance: tamping of the ballast bed, grinding of the rail surface, exchange of outer rails in curves, and exchange of turnout components (crossing, tongue rail, guide rail). The associated damage phenomena are the degradation of track geometry (vertical alignment of track), rail surface defects (mainly squats in straight sections and rolling contact fatigue (RCF) in curved sections), rail head side wear in curves, and wear, RCF and damage in turnout components.

These wear phenomena are assigned to impact stresses based on vehicle properties.

- The vertical impact is described using the P_2 force according to the British Rail group standard [53], covering the static axle load and the dynamic contribution of the unsprung mass at a certain speed due to a predefined track irregularity. The impact is set to a power of 3 based on the outcomes of ORE research [54] back in the 1980s. The damage stress collective is referred to as D1.
- Rail surface damage in straight sections is modelled with a combined stress, consisting of the P_2 force with an impact at a power of 1.2 ([54] 60% of the stress, D2) and the traction power value (TPV, D3). For the latter, the traction power is divided by the number of powered wheels and referred to the contact area between wheel and rail (influenced by the static axle load).
- The rail damage process in curves is indicated by the $T\gamma$ model [55][56][57][58] that covers RCF and rail wear at the same time. Based on this contact patch energy model, it is possible to simulate the RCF or wear contribution of every vehicle in a certain curve radius. The $T\gamma$ part is denoted by W_b in the Swiss formula (stress collective D4.1 for RCF and D4.2 for wear).
- For the turnout component's damage, a combined stress is calculated as a vector sum of a vertical impact force (again P_2) and a horizontal force (Y force). Both forces are calculated for the run of the vehicle through a turnout deviation with a radius of 185 m at a speed of 40 km/h. For the P_2 force, all axles are considered, and lateral forces are only counted for the leading axles of bogies. The stress collective is denoted as D5.

These damage laws are summed up in the Swiss wear formula (EQ 4):

$$C_V=k_{1_R}\times P_{2,V}{}^3+k_2\times P_{2,V}{}^{1,2}+k_3\times T_{pv}+k_{4_R}\times W_{b_R}+k_5\times\sqrt{(0.5\times P_{2,40km/h}{}^2+0.5\times Y_{R=185m}{}^2)} \qquad \text{EQ 4}$$

with

CV	Cost per vehicle kilometre
$P_{2,V}$	P_2 force at the speed V
T_{pv}	Traction power value
W_{bR}	Contact patch energy ($T\gamma$) in a certain R
$P_{2,40km/h}$	P_2 force at a speed of 40 km/h
Y_{R185m}	Y force in a 185 m radius
k_i	Cost calibration factors

Note: Within the SBB project "Wear Factor", a stress collective D6 was also defined for the reinvestment part (chapter 3.1.2.3), but not analysed further, due to the ministry's specification to only focus on maintenance.

The Swiss wear factor is well published [59][60] and since it will be implemented in 2017, the procedures for calculating vehicle input data and the classification of a new vehicle are published on the Swiss transport ministry's website. The approach was calibrated to the given network by using the standard element approach (see 3.1.1.4) and the vehicle collective assumed.

Figure 62 shows the accuracy of cost allocation for the Swiss TDM approach. The net-wide deviation shrinks to only plus/minus 10%. Compared to the approaches dealt with above, the Swiss TDM describes infrastructure properties as well as the speed influence and, in particular, the influence of the rolling stock. It becomes apparent that this approach is in another stage of accuracy. The high impact of speed due to the P_2 force on the speed-to-static-axle-load ration might be the reason for the comparably high deviations in the lines ML 2-3 and ML 3-2.

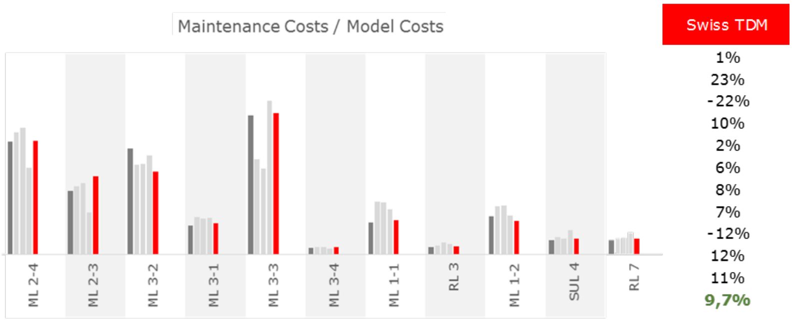

Figure 62 Accuracy of the Swiss TDM Approach

3.1.1.5.2 The Swedish TDM Approaches

The Swedish TDM was basically set up by vehicle engineers. This leads to the fact that vehicle properties are dealt with in more detail than infrastructure costs. Anyhow, the three main track damages (ballast degradation, rail RCF and wear, and component fatigue) are covered in a similar way. One major difference is that the Swedish approach is designed to cover reinvestment costs, and the components rail and sleeper are not changed within maintenance actions in general.

Wear phenomena is described using the following vehicle properties.

- The Q_{tot} force, with a static axle load contribution and two dynamic ones for different frequencies, covers vertical impact. The impact also refers to the ORE research set to a power of 3. As Q_{tot} is used, a quasi-static force component in curves can be added for the outer wheels.
- Component damage is referred to a combined stress consisting of the vertical force Q_{tot} and the quasi-static lateral force Y_{qst}. With reference to the ORE report D 141, the impact is covered by a power of 3.
- The $T\gamma$ model covers rail surface damage and wear, as the Swiss approach does.

The Swedish TDM is described by the formula EQ 3:

$$E_{a,Z}(R_j,T_a)=k_1\times T_Z\times\frac{1}{n_Z}\times\sum_{i=1}^{n_Z}Q^3_{tot\_i}+k_2\times(T_a+T_Z)\times\frac{1}{n_Z}\times\sum_{i=1}^{n_Z}\left[\sqrt{Q^2_{tot\_i}+Y^2_{qst\_i}}\right]^3+k_{34}\times T_Z\times\frac{\sum_{i=1}^{n_z}\left[f(\overline{F_v v})i\right]}{m_Z} \qquad \text{EQ 5}$$

with

Ea,Z(Rj,Ta)	Total accumulated deterioration of track within a certain curve zone for vehicle type Z, given as a marginal cost for all deterioration mechanisms due to accumulated tonnage Ta (SEK)
k1, k2, k34	Marginal average cost coefficients (calibrated against average annual marginal cost for deterioration). Subscript 1 for track settlement, 2 for component fatigue, and 34 (3 and 4 combined) for abrasive wear and RCF of rails
TZ	Tonnage or traffic volume for vehicle type Z during first year (gross-tonne-kilometre)
nZ	Number of axles on vehicle type Z
Qtot_i	Total vertical wheel load (usually low pass filtered at 90 Hz), i.e. Qstat + Qqst + Qd20Hz (+ Qdhf); subscript i related to axle i (kN)
Ta	Tonnage or traffic volume carried by the track since built or maintained (gross-tonne-kilometre)
Yqst_i	Quasi-static lateral wheel load or 'guiding force'; subscript i related to axle i (kN)
$f(\overline{F_v v})i$	Function relating wear and RCF to the friction energy dissipation

The approach has also been published several times [61][62][63].

As the Swedish approach does not consider turnout components explicitly and track components are not covered by the maintenance costs, the approach was modified a little: Q_{tot} and Y_{qst} were set to equivalent conditions of the Swiss TDM, i.e. 40 km/h in a radius of 185 m. In terms of model accuracy, this is a great improvement. With this formula change, the Swedish approach was calibrated to the network cost.

The result using the Swedish TDM is documented in Figure 63. Model accuracy is again much better than using the gross-tonne-kilometre approach, but slightly lower than applying the Swiss TDM (average deviation plus/minus 11%). The high impact of static axle load compared to speed level due to using the Q_{tot} force shifts costs from rather high-speed line segments to lower speed ones. This effect is particularly well shown by comparing the line segments ML 2-3 and ML 3-3 in both models.

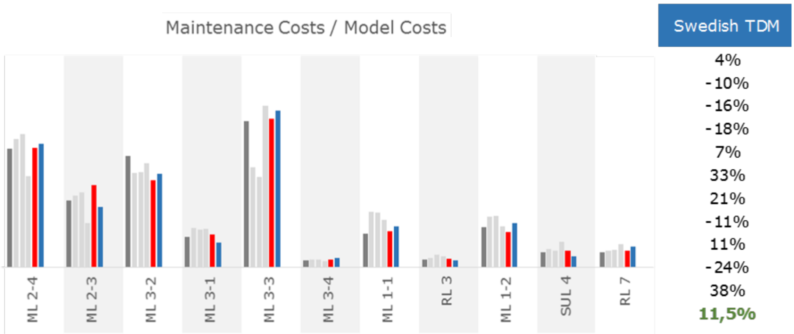

Figure 63 Accuracy of the Swedish TDM Approach

3.1.1.5.3 The British TDM Approaches

In the UK, the use of a TDM for the purpose of track access charging is already relatively established. Up to now, the UK has been the only country to implement its model in the charging scheme. The approach was modified for the control period 5 when the existing formula was recalibrated (and partly restructured) and the approach of curving classes based on the $T\gamma$ model was added.

This approach is slightly more general than the ones shown above: Total wear and tear costs of track (including reinvestment parts) are covered by one formula including axle load, speed, and unsprung masses. The $T\gamma$ part is treated separately and is comparable to what has already been shown in the Swiss and Swedish models.

The British TDM is based on equations 4 and the Tγ function:

$$D_V = C_t \times (0.473 \times e^{(0.133 \times A)} + 0.015 \times S \times U - 0.009 \times S - 0.284 \times U - 0.442) \times GTM \times axles$$ EQ 6

with

Ct Coefficient Ct=0.89 for locomotive-hauled passenger stock and multiple units, and 1 for all other vehicles
A axle load (tonnes)
S operating speed (miles/hour)
U unsprung mass (tonne/axle)
GTM gross-tonne-miles

The approach is published in the documents of the Office of Rail Regulation in the UK [64][65].

The approach is well suited to cost recovery on the single line segments. Even though it is only intended to cover speeds of up to 100 mph (160 km/h), the results for ML 2-4 and 2-3 indicate that speeds of up to 200 km/h can also be covered, as Figure 64 shows.

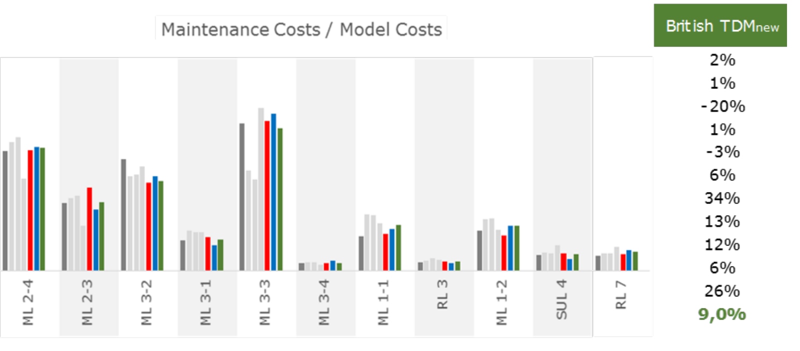

Figure 64 Accuracy of the British TDM Approach

3.1.1.5.4 Comparison of the TDM Approaches

In terms of model accuracy, it seems that there is little difference between the models. However, a consideration of the details and single vehicles reveals that this is not the case. All the approaches allocate the track costs very differently to the common and most used gross-tonne-kilometre approach (grey bar in Figure 65). While the Swedish and the British approaches shift the costs towards high axle loads with almost no impact of the speed level, the Swiss approach is different. In the SBB model, higher axle load also counts more, but speed has a massive influence (due to the P_2 force approach used). Additionally, the term concerning turnout component damage also allocates costs concerning this damage to empty freight wagons (with very low axle loads). The costs per gross-tonne-kilometre are ultimately even higher than for a full wagon.

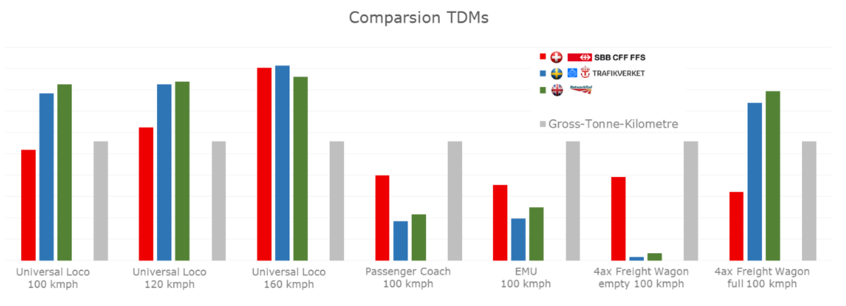

Figure 65 Comparison of TDMs

In addition to the general cost allocation towards lines, the influence of axle load versus speed is difficult to determine in a mixed traffic network. It is only possible to evaluate whether one of these two parameters is constant while the other is changing. This is only possible by analysing lines covering totally homogenous traffic or vehicles. Experience of this is limited, as pure freight lines do not normally face relevant speed differences. The only reference is pure high-speed operation on ballasted track, which can only be found in France (with enough track length to gather statistical confidence). Furthermore, the influence of line speed on track alignment deterioration should be considered when analysing recording car data.

The influence of speed on track geometry deterioration and therefore tamping demand was subject to a study carried out for the new HS2 line in UK. [66] As very high speeds are not covered by Austrian experience, the P2 formula of the Swiss approach had been used to validate Austrian data. Figure 66 shows the increasing force-level of P2 due to higher speeds. It is assumed that the force is directly linked with track geometry's deterioration.

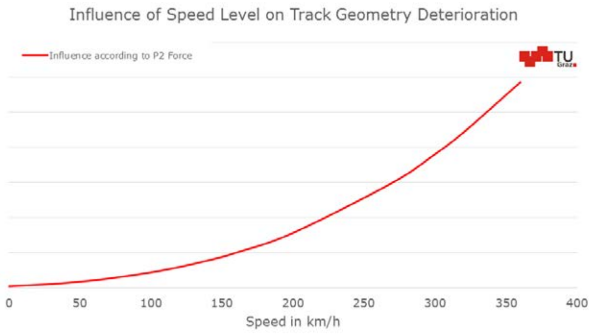

Figure 66 Influence of Speed on Track Geometry Deterioration

In Austria, intensive research on track geometry deterioration has been carried out for more than 10 years. However, the experiences of TU Graz do not cover these high-speed ranges, as mentioned above, although the influence of higher speed levels was also investigated on the Austrian network. Hummitzsch [67] depicts that it is not inconsequential to show the influence of speed for ÖBB tracks. In an overall statistical analysis for speed ranges from 100 km/h to 160 km/h, the influence seems to be insignificant, since results vary on a large scale from "no influence" to almost "exponential influence" .

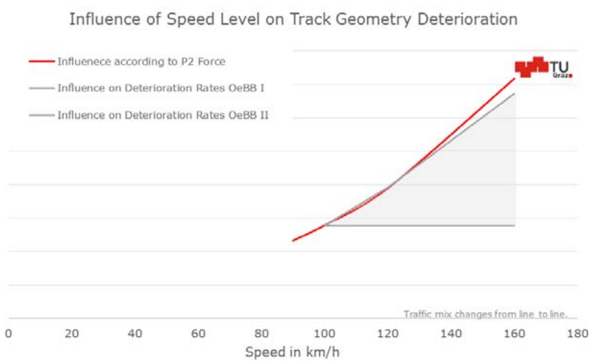

Figure 67 Influence of Speed Level on Track Deterioration on Austrian Tracks I

This is reasonable, as only a limited number of trains are actually operated at high speeds in Austria. In a mixed traffic system, speeds of more than 100 km/h are reserved for passenger trains. Higher speeds (140 km/h or more) are operated by fast, long-distance passenger trains, as an exception. An estimated influence of a mixed traffic collective, recalculated with the Swiss wear factor (P_2 force and exponent 3 for the axle load influence) provides a function for the influence of speed, which is somewhere within the evaluated values (Figure 68).

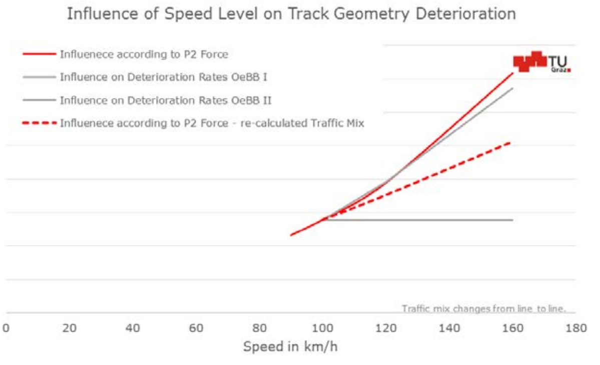

Figure 68 Influence of Speed Level on Track Deterioration on Austrian Tracks II

Hummitzsch evaluated the influence of speed on the track geometry deterioration for a set of data that is supposed to have uniform traffic. For this (small) sample of deterioration data, Hummitzsch shows a regression function following an exponential form. In his thesis, he presents two formulas for the regression function, although one is only a simplification of the other. The exponential function follows the P2 force characteristic in the lower speed ranges of up to 160 km/h (this is the experience covered) as shown in Figure 69. If extrapolating towards higher speeds, the function shows less increase of track deterioration if this is equal to the applied force depicted by the P_2 force. For higher speeds, the results are significantly different as presented in Figure 66, but these speeds are not covered by any Austrian track, which is important to note.

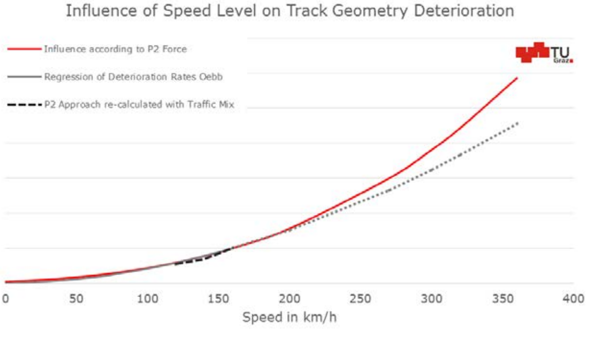

Figure 69 Influence of Speed Level on Track Deterioration on Austrian Tracks III

The Austrian regression corresponds to the P_2 approach in the speed ranges covered in Austria. Results have been compared with French experience as well.

These results show that the assumption made in Switzerland is fairly good. The Swedish approach (and also the British one, but this refers to the KTH model in this particular case) includes only a very limited influence of speed. It is possible – at least for the British case – that very poor subsoil conditions make the axle load critical. This could be researched further. Whether the same is true for Swedish tracks cannot be proven in this paper either.

To return to the model accuracy on different line segments (Figure 64): In addition to the details provided on the influence of speed, it seems that a hybrid model including the detailed Swiss approach focused on track maintenance and the general reference to the vehicle weight and a (little) less influence of speed could increase the accuracy. This hybrid model is analysed in 3.1.1.5.5.

3.1.1.5.5 The Hybrid TDM Approach

Following on from the descriptions above, a hybrid TDM was derived from the existing

$$C_V = k_{1_R} \times T \times \frac{{P_{2mod,V}}^3}{n_a} + k_2 \times T \times \frac{{P_{2mod,V}}^{1.2}}{n_a} + k_3 \times T \times \frac{T_{pv}}{n_a} + k_{4_R} \times T \times \frac{W_{b_R}}{n_a} + k_5 \times T \times \frac{\sqrt{\left(0.5 \times {P_{2mod,40km/hh}}^2 + 0.5 \times {Y_{R185m}}^2\right)}}{n_a} \qquad \text{EQ 7}$$

with

C_V	Cost per vehicle kilometre
T	Tonnage of the vehicle
n_a	Number of axles
$P_{2mod,V}$	Modified P_2 force (50% better track quality) at the speed V
T_{pv}	Traction power value
W_{bR}	Contact patch energy ($T\gamma$) in a certain R
$P_{2mod,40km/h}$	Modified P_2 force at a speed of 40 km/h
Y_{R185m}	Y force in a 185 m radius
k_i	Cost calibration factors

The hybrid model – as expected – provides slightly better model accuracy than the other approaches. Figure 70 shows that the recovered costs on the line segments are somewhere between the Swiss and the Swedish level.

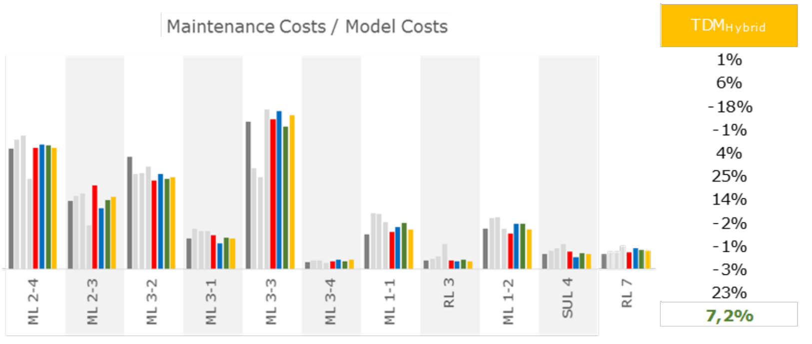

Figure 70 Accuracy of the Hybrid TDM Approach

Combining the Swiss and the Swedish approach generally leads to vehicle kilometre costs in-between the two cost levels. This is not the case for locomotives, as the influence of high axle load, speed, and unsprung mass can lead to the highest cost levels at high speeds in the hybrid TDM (Figure 71).

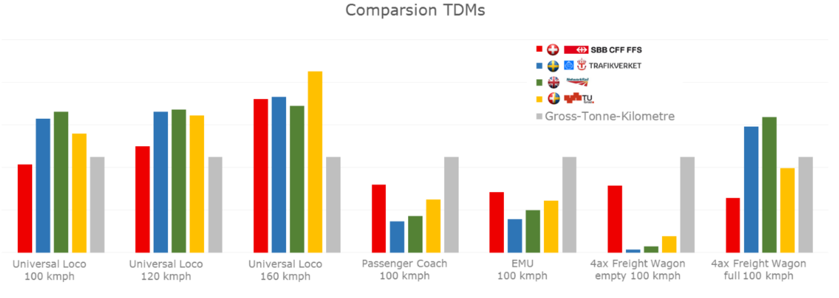

Figure 71 Comparison of TDMs II

3.1.1.5.6 TDM Approaches – Summary I

The evaluations of TDMs provide clear evidence of the usefulness of such models. On the one hand, a TDM alone makes it possible to calculate *"the cost that is directly incurred"* by a train run. On the other hand, it solves one of the main problems that separation of RUs and IMs created in the railway system: With the transfer of saved or increased infrastructure costs back to the vehicle operator (RU), the consequences of "track-friendly" vehicles and "track murderers" can be forwarded to the decision-maker for some kind of technology. Without this transfer, innovative, "track-friendly" technology will not be put into operation, as these technologies result in higher first costs of the vehicles in most cases.

These two facts lead to the next principle for a proper TAC system:

Principle III: Wear-based Charging

Wear-based means vehicle-based, of course. There is no way to approximate the wear costs of track without using a track deterioration model that consists of vehicle properties as well as infrastructure and operational properties (speed). The increased complexity is justified by much better model accuracy.

Besides the TAC topic, TDMs provide a great opportunity for the IMs to go into more detail in their asset monitoring. The P_2 force in the Swiss TDM (and accordingly the hybrid TDM) and – to a lesser degree – the Q_{tot} in the Swedish TDM include a technical description of increasing vertical forces due to a lower level of track quality. The track failure is an input figure in these calculations.

In day-to-day asset management, track deterioration is the focus. Varying the track failure in the formulas from lower to higher failures could be a very interesting aspect for the IM's track asset management departments: It is technically impossible to have increasing loads and linear track geometry deterioration. Numerous analyses of track quality behaviour show that track very likely deteriorates following an e-function. [67][68]On the other hand, there is also an indication that vertical track geometry can be properly described by a linear regression. [69][70] Perhaps the TDMs will enable the deterioration process to be understood better. Figure 72 shows the deterioration of track as a function of an increasing load. A linear deterioration of track is assumed within one time increment. The load (sum of the P_2 forces of all wagons) is then recalculated, resulting in a higher loading. The deterioration rate of the first segment is multiplied by the increased load factor. Repeating this process leads to an over-linear loss of track geometry or an over-linearly growing track failure. The exponential regression to the points in Figure 72 fits quite well, showing a slight overestimation of the track failure growth at low quality levels. For high quality levels, the behaviour is described almost perfectly with a linear regression in both cases analysed (Swiss TDM and hybrid TDM).

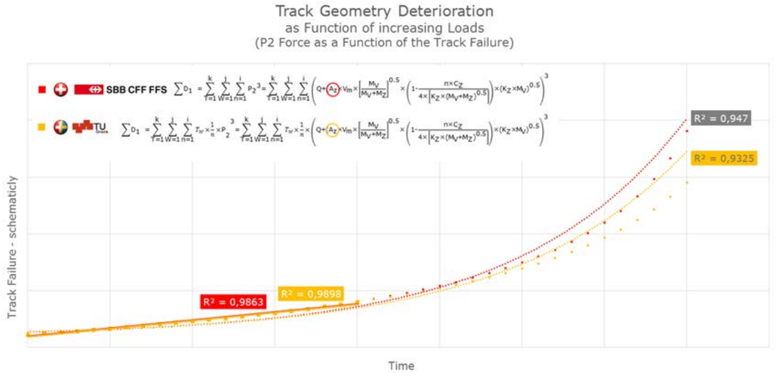

Figure 72 Track Geometry Deterioration – as a Function of Increasing Loads

Such track behaviour can be found in reality. Figure 75 shows two segments of the Austrian network (ÖBB data assembled in the TU Graz data warehouse [71]). The left part of Figure 73 shows a track at a high quality level whose behaviour corresponds to a linear regression for almost eight years, before it begins to follow a strongly over-linear deterioration (the yellow lines inserted are the ones shown in Figure 72). The right part depicts a track with much poorer quality. High track irregularities induce high dynamic forces in the TDMs, leading to a fast deterioration process. It is very likely that the quality decrease after the tamping actions (green vertical lines) follows the steep part of the e-function.

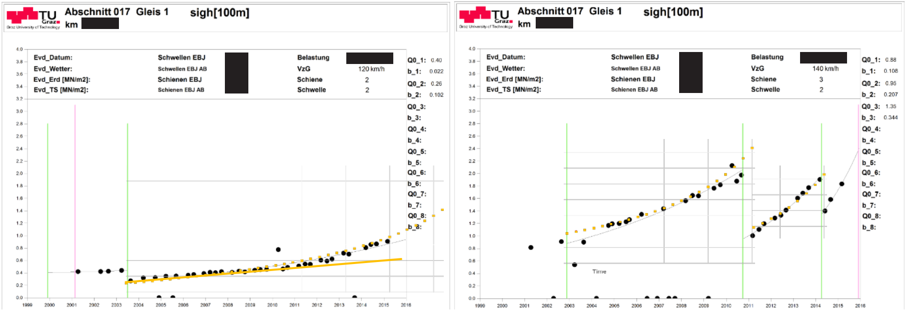

Figure 73 Track Geometry Deterioration – Reality and Theory

Track deterioration analysis is not the topic of the current paper, but allows for research in the coming years. A validation of the TDMs is difficult, in any case. This also applies for the other parts of the formulas. Improved knowledge will make it possible to study this topic in more detail in the future.

To return to principle II: So far, the TDMs assure that track radius is considered. When it comes to turnouts, the TDMs are still average models. This is partly due to missing data. In Switzerland, the TDM is to be implemented without taking into account line characteristics. Austria, for example, has been following a line strategy since the beginning in the early 1990s. By charging on a line-based approach (which principle II indicated was necessary), the number of turnouts can be incorporated. Turnouts trigger the track costs to a high degree (see chapter 2.4.1), due to their number but also depending on their size. Since the Swiss and the hybrid TDM foresee terms dedicated to turnouts, it is easy to modify them. The Swedish and British models do not specify turnout component damage separately (although this was carried out by a modification in chapter 3.1.1.5.2 for the Swedish one). The following chapter considers possible adjustments to the TDMs in order to further improve model accuracy.

3.1.1.5.7 Improved TDM Approaches – Turnout Factor and New Line Factor

Turnout Factor

Information on the asset types is available at most IMs. For the calculations so far, the number and size of the turnouts have already been used (in the Standard Element Approach and in the cost calibration of the TDMs) to describe the track costs on the different lines. This information is extracted and transformed in a line-specific factor.

The number of turnouts per kilometre and line is depicted in Table 3. The type of turnout used is also specified. On average, the network consists of 0.873 turnouts per track kilometre. This value is overridden and underridden by more than 50% in different line segments.

	R1600/2600 S	R1200 S	R1200 C	R760 S	R500 S	R500 C	R300 S	R300 C	R190 S	R190 S	Number of Turn-outs [#]	Section Length [km]	Turnouts per Track kilometre [#/km]
ML 2-4		13	5		20	13	2				53	60	0.883
ML 2-3	2	19			15		2				38	50	0.760
ML 3-2		4	19		25	29	2	6	2	1	88	70	1.257
ML 3-1		5	7		9	11	2	2			36	30	1.200
ML 3-3		0	1		20	24	7	6	6	2	66	80	0.825
ML 3-4		1	1		1	2					5	10	0.500
ML 1-1		4		2	16	3	16	1	9		51	70	0.729
RL 3					1	2	1		2		6	15	0.400
ML 1-2		14	4		23	8	1		3		53	80	0.663
SUL 4		4			24	6	8	2	8	3	55	35	1.571
RL 7					2	4	6	4			16	35	0.457
Sum	2	64	37	2	156	102	47	21	30	6	467	535	0.873

Table 3 Number and Size of Turnouts per Line

Chapter 2.4.1shows that maintenance costs in turnouts vary due to several main effects: turnout size, its geometry in track, the superstructure used, and substructure quality. The latter two are still covered indirectly via the costs defined above (3.1.1.4), while the size and the geometry is indicated explicitly. The term assigned to turnouts in the TDMs describes the damage of turnout components, while tamping and grinding is covered by the other terms.

While the costs for exchanging the components vary with the size (simply due to the length), the geometry influences the frequency of the component exchange. These two effects are summarised using their cost weights and then normalised to the costs for a straight R 300 turnout. These cost factors are multiplied later with the number of turnouts to generate a cost-weighted Turnout Factor (TF). The results are given in Table 4.

	R1600/2600 S	R1200 S	R1200 C	R760 S	R500 S	R500 C	R300 S	R300 C	R190 S	R190 S	Number of Turn-outs [#]	Section Length [km]	Turnouts per Track kilometre [#/km]
	2.10	1.34	2.69	1.12	1.00	2.00	0.89	1.77	0.79	1.58			
ML 2-4	0.00	17.47	13.44	0.00	20.00	26.00	1.77	0.00	0.00	0.00	78.69	60	1.312
ML 2-3	4.19	25.54	0.00	0.00	15.00	0.00	1.77	0.00	0.00	0.00	46.51	50	0.930
ML 3-2	0.00	5.38	51.08	0.00	25.00	58.00	1.77	10.64	1.58	1.58	155.04	70	2.215
ML 3-1	0.00	6.72	18.82	0.00	9.00	22.00	1.77	3.55	0.00	0.00	61.86	30	2.062
ML 3-3	0.00	0.00	2.69	0.00	20.00	48.00	6.21	10.64	4.74	3.16	95.45	80	1.193
ML 3-4	0.00	1.34	2.69	0.00	1.00	4.00	0.00	0.00	0.00	0.00	9.03	10	0.903
ML 1-1	0.00	5.38	0.00	2.25	16.00	6.00	14.19	1.77	7.11	0.00	52.71	70	0.753
RL 3	0.00	0.00	0.00	0.00	1.00	4.00	0.89	0.00	1.58	0.00	7.47	15	0.498
ML 1-2	0.00	18.82	10.75	0.00	23.00	16.00	0.89	0.00	2.37	0.00	71.83	80	0.898
SUL 4	0.00	5.38	0.00	0.00	24.00	12.00	7.10	3.55	6.32	4.74	63.09	35	1.803
RL 7	0.00	0.00	0.00	0.00	2.00	8.00	5.32	7.10	0.00	0.00	22.42	35	0.641
Sum											467	535	1.241

Table 4 Turnout Factors

These factors can be incorporated into the TDMs by adding them as operators to the turn-out term of EQ 4 and EQ 7.

Swiss TDM:

$$C_V = k_{1_R} \times P_{2,V}^{\ 3} + k_2 \times P_{2,V}^{\ 1,2} + k_3 \times T_{pv} + k_{4_R} \times W_{b_R} + k_5 \times TF_L \times \sqrt{\left(0.5 \times P_{2,40km/h}^{\ 2} + 0.5 \times Y_{R185m}^{\ 2}\right)} \qquad \text{EQ 8}$$

Hybrid TDM

$$C_V = k_{1_R} \times T \times \frac{P_{2mod,V}^{\ 3}}{n_a} + k_2 \times T \times \frac{P_{2mod,V}^{\ 1.2}}{n_a} + k_3 \times T \times \frac{T_{pv}}{n_a} + k_{4_R} \times T \times \frac{W_{b_R}}{n_a} + k_5 \times TF_L \times T \times \frac{\sqrt{\left(0.5 \times P_{2mod,40km/h}^{\ 2} + 0.5 \times Y_{R185m}^{\ 2}\right)}}{n_a} \qquad \text{EQ 9}$$

with

TF_L Cost-weighted turnout factor per line

As the cost-weighted average number of turnouts (1.241 in Table 4) is higher than the unweighted one (0.873 in Table 3), the cost calibration factor k_5 must be recalibrated in order to keep turnout costs constant.

The incorporation of the turnout factor improves the model accuracy by almost 50% for the hybrid TDM, and by 30% for the Swiss TDM (Table 5, Figure 74).

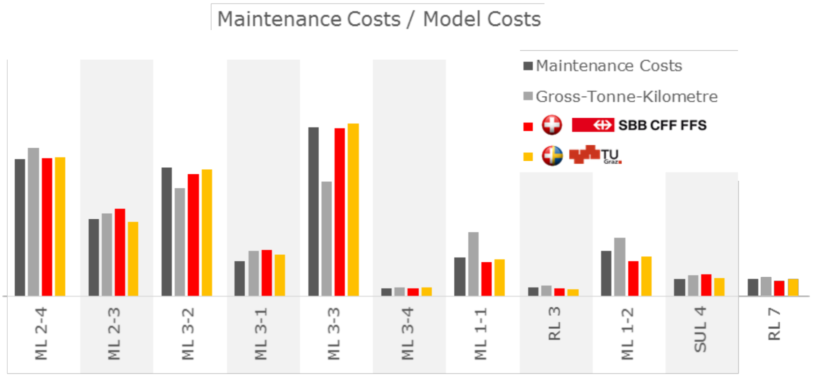

Figure 74 Model Accuracy TDMs with Turnout Factor

	gtkm	Swiss TDM	TDM_{Hybrid}
ML 2-4	8%	0%	1%
ML 2-3	7%	13%	-3%
ML 3-2	-15%	-5%	-1%
ML 3-1	30%	31%	19%
ML 3-3	-32%	0%	2%
ML 3-4	14%	-5%	14%
ML 1-1	64%	-13%	-6%
RL 3	19%	-16%	-22%
ML 1-2	27%	-24%	-13%
SUL 4	21%	26%	9%
RL 7	15%	-10%	2%
	21%	**7,6%**	**4,3%**

Table 5 Model Accuracy TDMs with Turnout Factor

This approach makes it possible to explain the high gross-tonne-kilometre value of the line segment ML 2-1 that had been excluded from the calculation until now due to that fact (Figure 56). This line segment is the access to a major passenger station. This indicates that there are numerous turnouts in main track (TF 4.00). Additionally, more than 150 turnouts are spread across the adjunct tracks on the only 5 kilometre-long line section. The turnout factor was multiplied by 3 to cover this additional number of turnouts. With this modification, the TDMs recover the costs on the section (Figure 75).

<u>New Line Factor</u>

A further two considerably longer high-loaded lines were defined as outliners in Figure 56. One of the sections is a brand-new, double-tracked line with 25% slab track. According to the evaluations shown in chapter 2.4.1, this quarter of the line must not be considered entirely in the D1 damage part of the TDMs, as it is mainly assigned to ballast bed maintenance. The track length was reduced for this single TDM term by 75% (only rail pad exchange is retained as cost factor for D1). For the rest of the track, the "new line" standard element must be used to describe costs (the line has no radii below 1,000 m, so rail wear is not the main cost driver). This and the fact that the line is within the first quarter of its service life makes it necessary to reduce the k_1 cost calibration factor to 25%. The second line is the parallel string to the new line and was partly upgraded when the new line was opened. k_1 is reduced to 0.4 accordingly.

This procedure is limited to a few line segments. In particular, a high percentage of tunnels and bridges – where the superstructure is often built as slab track – indicates that a line needs this modification in the TDM. IMs with entire slab track lines (e.g. DB Netz AG in Germany) even have parts of the network that do.

Cost recovery (model accuracy) is still excellent, including for the added, modified lines (greenish background in Figure 75).

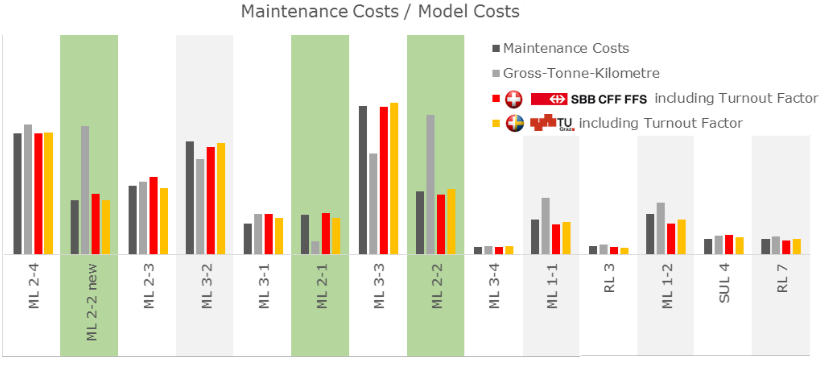

Figure 75 Model Accuracy TDMs with Modified Lines

3.1.1.6 Cost Recovery

The cost recovery of all the approaches on the excluded lines is poor. As the marginal cost level was defined with high-loaded line segments, the higher cost on the low-loaded lines cannot be covered. The gross-tonne approach recovers the missing costs on these lines by the high revenues on the lines ML 2-2 and ML 2-2 new. If the marginal cost level is set to 50% here, the total cost recovery is similar to those of the TDMs. Cost recovery of the entire network is around 85% for all the approaches.

It should be noted once again that these low-loaded lines might have maintenance costs that do not occur on main lines. These lines have an old, light superstructure, and on some lines there is a high number of wooden sleepers. Spot maintenance and life-prolonging maintenance is to be expected on these lines. A not insignificant part of the maintenance will be time-bound, anyhow. Parts of the load-dependent, life-prolonging maintenance may be covered by the renewal term (chapter 3.1.2).

3.1.2 Reinvestment Costs

Generally, the costs of reinvestment are capitalised. In bookkeeping, asset service life occurs as a fixed value. As the utilisation of the asset is not considered (or only very roughly, e.g. high-loaded and low-loaded tracks), it is impossible to extract the marginal cost. A model is required to show the marginal part of the reinvestment by using calculatory depreciation. The calculatory depreciation is influenced by a number of boundary conditions, of which transport volume is only one. The UK's approach to the marginal cost of track renewal (95% of rail, 25% of sleepers, 30% of ballast, and 25% of turnouts [47]) is very general and depicts average values. In a general strategy of total reinvestment, the track components are not renewed separately, but rather the asset track is renewed as an entire structure.

The optimal point in time for track renewal can only be calculated by using the procedure described in chapter 2.1. Depending on the loading, the track radius, and the superstructure used, different components trigger the increase in maintenance and therefore the economic necessity of reinvestment. The methodology presented in chapter 2.1 does not therefore address single components, but rather the renewal cost of the entire track structure. The different service lives are the result of long-term LCC evaluations carried out in Austria, and their basic logic has been confirmed at other IMs. It should be noted that the service lives used in this chapter are validated by comparing the results of the standard elements track and track reinvestment projects over a five-year period [72]. Whenever depreciation is addressed in the following chapters, it is always the calculatory depreciation and not the fixed bookkeeping depreciation.

Theoretically, the variable part of depreciation is the delta between the depreciation at non-usage and the depreciation at intensive usage. Equations EQ 10 and EQ 11 illustrate this relation.

$$\text{Variable Depreciation} = \frac{\text{(Replacement Costs-Residual Value)}}{\text{Service Life}_{\text{Intensive Usage}}} - \frac{\text{(Replacement Cost-Residual Value)}}{\text{Service Life}_{\text{Non-Usage}}} \qquad \text{EQ 10}$$

or simply

$$\text{Variable Depreciation} = \text{Depreciation}_{\text{Non-Usage}} - \text{Depreciation}_{\text{Intensive-Usage}} \qquad \text{EQ 11}$$

Figure 76 shows the relation between service life and usage.

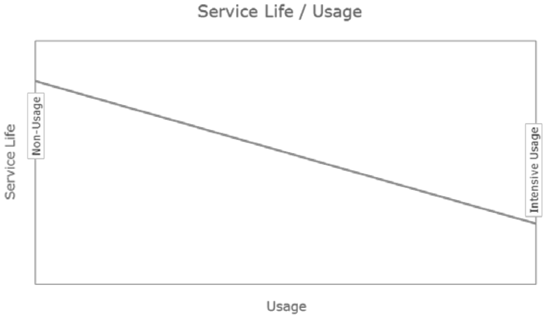

Figure 76 Service Life as Function of the Usage

Depreciation is defined by a 1/n function. By adding this function to Figure 76, the variable part of the depreciation can be seen easily.

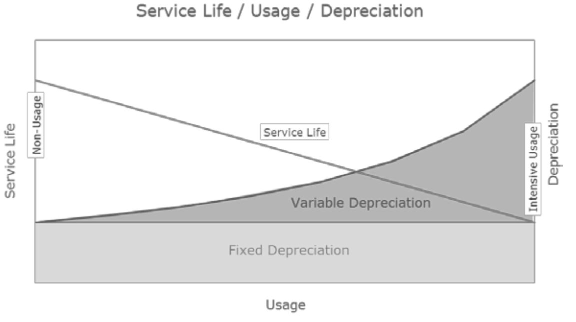

Figure 77 Service Life and Depreciation as Function of the Usage

For infrastructure assets, the minimum depreciation is not linked to the non-usage, but rather to a certain transport volume. This volume depends on various technical boundary conditions. An understanding of the technical background is a precondition for a proper evaluation of the marginal cost level of renewal cost. The interaction between loading, superstructure, maintenance, and service life is essential for the calculation of the variable part of depreciation.

3.1.2.1 Service Life of Track

To return to Figure 37: The depreciation (green bar) increases with an increasing transport volume. In order to analyse the depreciation in detail, it is necessary to determine which component is triggering the renewal of track.

Rails very rarely trigger a total renewal of track, as they can be changed easily and without an impact on the track structure (component at the top of the structure). In the case of 60E1 rails, in particular, fatigue is not an issue on mixed-traffic European railway lines. The fatigue limit for this rail profile is higher than 2 billion gross-tonnes [73], so that rails have service lives higher than 50 years even on very high-loaded lines.

Concrete sleepers are supposed to have a maximum service life of 50 years (even though this value is, of course, overridden in certain cases). Since exchanging sleepers is a very costly measure, and the asset quality delivered by this track work is poor, sleepers can be decisive in some cases. In the case of wooden sleepers, the maximum service life is set to 35 years on average (for good subsoil and drainage conditions).

On curved tracks, the lateral force level at the rail bearing and the fasteners is high. In addition to increased maintenance for the fasteners and the rail pads, this ultimately leads to a loss of force transmission, and makes it necessary to change the sleepers.

A ballast bed is also crucial for the entire track system. Due to the loading, the ballast bed loses geometric stability and has to be lifted, tamped, and stabilised whenever limits are reached. The forces applied to the ballast lead to grain fracturing and abrasion. The grain distribution is shifted toward higher percentages of fine material (ballast fouling). This leads to a loss of elasticity and a reduced draining functionality. Both of these are unfavourable for the track structure: The first effect induces higher loads to rails and sleepers, as the load distribution by the bending-curve of the rail towards a higher number of sleepers is hindered. Moreover, the concentrated force transmission leads to higher pressures on the substructure. These effects are crucial, especially in combination with the reduced ability of water drainage. The initiated pumping effect due to loading and unloading by the train axles pushes up cohesive material into the ballast bed (mud holes). If the ballast bed dries out, a very stiff structure remains, boosting the effect of overloaded components. To prevent these effects, ballast cleaning or exchange is carried out. Both these actions are very costly and are only worthwhile if the sleepers and rails have a sufficient remaining service life.

In summary, either sleeper or ballast issues trigger the renewal of track in technical terms. In order to transfer this knowledge to the topic of variable depreciation, the track cost must be analysed.

3.1.2.2 Evaluating the Marginal Cost Level – Renewals

For straight concrete sleeper tracks, the maximum service life of 50 years (sleeper) is only possible for very low transport loads. The analyses demonstrate this limit to be around 8,000 gross-tonnes per track daily (3 million gross-tonnes per year). This service life leads to the lowest depreciation possible, as lower loading does not increase service life. Transferring this into Figure 77 allows the variable part of track renewal cost as a function of transport volume to be determined (Figure 78).

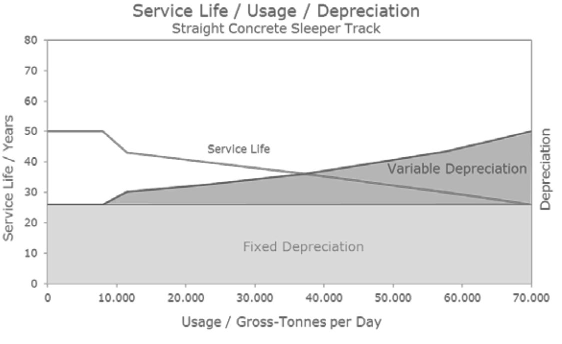

Figure 78 Variable Depreciation Concrete – Straight Sleeper Tracks

The situation is different for wooden sleeper tracks. The maximum life expectancy for wooden sleepers is only 35 years. This means a generally higher depreciation due to a shorter service life, on the one hand, and slightly higher material costs, on the other. In addition, the variable part of the depreciation is lower. As the maximum service life is already around 15 million gross-tonnes per year, only higher transport volumes involve variable costs. Figure 79 shows this effect.

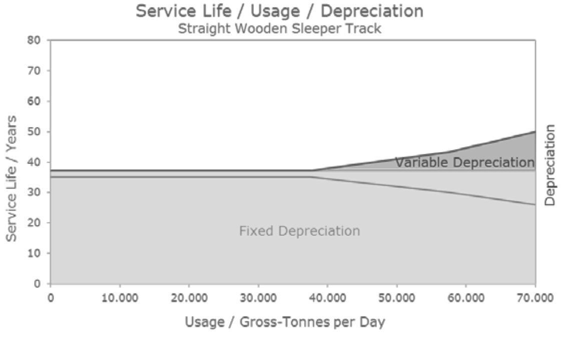

Figure 79 Variable Depreciation Concrete – Straight Wooden Tracks

An analysis of different superstructures shows that the rates of variable depreciation and the absolute values change. Concrete sleepers with soft pads have longer service lives due to improved load distribution in the ballast bed. Consequently, variable parts of the depreciation decrease. Slab track is only considered to have fixed depreciation, as the service life of the concrete superstructure does not change with an increasing transport load.

Not only the superstructure, but also the track alignment influences service life and therefore depreciation. Figure 80 shows the impact of the radius (which is small in this case) on the variable depreciation. Service life decreases strongly with a rising transport volume. This leads to high variability of depreciation at high loads.

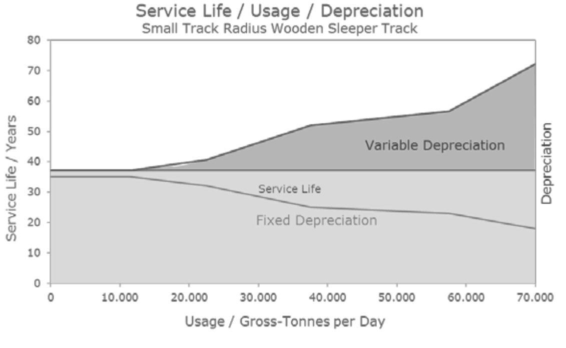

Figure 80 Variable Depreciation Concrete – Curved Wooden Tracks

Table 6 provides all the values used in the evaluations for tracks in chapter 3.1.2.2. Similar calculations have been made for turnouts.

		60E1	60E1			54E2		49E1	
		Slab Track	Concrete	Concrete USP	Wooden	Concrete	Wooden	Concrete	Wooden
25 million Gross-Tonnes per Year	R>600m	0%	40%	28%	26%	53%	43%	56%	46%
	400m<R<600m	n.a.	47%	42%	34%	56%	46%	58%	49%
	250m<R<400m	n.a.	51%	48%	40%	58%	49%	58%	49%
	R<250m	n.a.	n.a.	n.a.	49%	n.a.	54%	n.a.	54%
20 million Gross-Tonnes per Year	R>600m	0%	30%	16%	14%	42%	29%	44%	31%
	400m<R<600m	n.a.	35%	30%	20%	44%	31%	47%	34%
	250m<R<400m	n.a.	42%	38%	29%	49%	37%	51%	40%
	R<250m	n.a.	n.a.	n.a.	34%	n.a.	43%	n.a.	46%
15.5 million Gross-Tonnes per Year	R>600m	0%	16%	0%	0%	26%	9%	26%	9%
	400m<R<600m	n.a.	21%	14%	3%	28%	11%	30%	14%
	250m<R<400m	n.a.	35%	32%	20%	40%	26%	19%	0%
	R<250m	n.a.	n.a.	n.a.	29%	n.a.	37%	n.a.	40%
8 million Gross-Tonnes per Year	R>600m	0%	7%	0%	0%	16%	0%	19%	0%
	400m<R<600m	n.a.	16%	6%	0%	21%	3%	23%	6%
	250m<R<400m	n.a.	21%	28%	3%	30%	14%	33%	17%
	R<250m	n.a.	n.a.	n.a.	9%	n.a.	20%	n.a.	23%
4 million Gross-Tonnes per Year	R>600m	0%	0%	0%	0%	0%	0%	0%	0%
	400m<R<600m	n.a.	7%	2%	0%	7%	0%	7%	0%
	250m<R<400m	n.a.	12%	24%	0%	12%	0%	12%	0%
	R<250m	n.a.	n.a.	n.a.	0%	n.a.	0%	n.a.	0%
3 million Gross-Tonnes per Year	R>600m	0%	0%	0%	0%	0%	0%	0%	0%
	400m<R<600m	n.a.	0%	0%	0%	0%	0%	0%	0%
	250m<R<400m	n.a.	0%	0%	0%	0%	0%	0%	0%
	R<250m	n.a.	n.a.	n.a.	0%	n.a.	0%	n.a.	0%

Table 6 Variable Depreciation as a Percentage of Total Depreciation – Track

The iTAC network consists of different superstructures. The evaluated percentages of variable depreciation were applied, taking into consideration the superstructure, track radius and gross-tonnage. Figure 81 shows both maintenance (grey bars) and variable depreciation (black bars) on the lines of the iTAC network. High-loaded lines naturally incorporate higher proportions of variable depreciation, and some minor regional lines face a total tonnage below 3 million gross-tonnes per year and their renewal costs are therefore not considered.

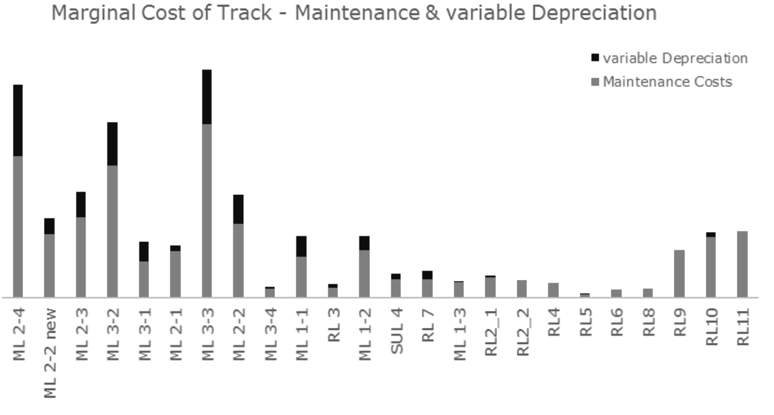

Figure 81 Maintenance and Variable Depreciation on iTAC Lines (Track incl. Turnouts)

The costs of turnouts are equally distributed with the track kilometres. It is not feasible – and much too detailed – to treat them according to their exact location. On the other hand, the number and size of turnouts are relevant to the costs. Therefore, as in chapter 3.1.1.5.7, a turnout factor is calculated for every line segment. This factor is different from the one calculated for the turnout component exchange. The relation between the different reinvestment costs is a little larger than that between the maintenance costs. On the other hand, there is no difference in service life, regardless of whether the turnout is situated in a curved or a straight track section. Table 7 shows the values for the turnout sizes and the turnout factors for the calibration lines.

	R1600/2600	R1200	R760	R500	R300	R190	Number of Turnouts [#]	Section Length [km]	Turnouts per Track-km [#/km]
	2.20	1.46	1.29	1.00	0.88	0.71			
ML 2-4	0.00	17.47	0.00	26.00	1.77	0.00	78.69	60	1.018
ML 2-3	4.19	25.54	0.00	0.00	1.77	0.00	46.51	50	0.979
ML 3-2	0.00	5.38	0.00	58.00	1.77	1.58	155.04	70	1.384
ML 3-1	0.00	6.72	0.00	22.00	1.77	0.00	61.86	30	1.370
ML 3-3	0.00	0.00	0.00	48.00	6.21	3.16	95.45	80	0.783
ML 3-4	0.00	1.34	0.00	4.00	0.00	0.00	9.03	10	0.593
ML 1-1	0.00	5.38	2.25	6.00	14.19	0.00	52.71	70	0.698
RL 3	0.00	0.00	0.00	4.00	0.89	0.00	7.47	15	0.354
ML 1-2	0.00	18.82	0.00	16.00	0.89	0.00	71.83	80	0.754
SUL 4	0.00	5.38	0.00	12.00	7.10	4.74	63.09	35	1.501
RL 7	0.00	0.00	0.00	8.00	5.32	0.00	22.42	35	0.424
Sum							498	535	0.923

Table 7 Turnout Factors – Renewal Cost

3.1.2.3 Allocation of Renewal Cost

The cost allocation procedure is similar to that for maintenance costs. Four approaches have been analysed:

- the gross-tonne-kilometre approach;
- the Swiss TDM;
- the UK TDM, and
- the hybrid TDM.

The Swedish TDM is not considered, as it is partly covered by the hybrid one.

While the gross-tonne approach does not need any explanation, since costs are simply divided by the gross-tonne-kilometres, the damage processes of the TDM approaches do.

In the UK's approach, there is no additional part in the formula. The approach was originally calibrated for both cost proportions. In the following evaluation, however, the variable depreciation part is analysed separately.

The SBB wear factor comprises another damage term, which is not foreseen in the Swiss TAC application, as only maintenance costs are charged. This stress collective (D6) is very similar to the one used in the Swedish approach and is once again based on the ORE studies [54]. It describes a damage process where a combined force leads to component damage with a power of 3.

$$C_{V,D6}=\left(\sqrt{\left(f_{61,R}\times P_{2,V}{}^{2}+f_{62,R}\times Y_{R}{}^{2}\right)}\right)^{3} \qquad \text{EQ 12}$$

with

$C_{V,D6}$ Cost per vehicle kilometre – renewal cost (D6)
$P_{2,V}$ P_2 force at the speed V
Y_R Combined lateral force including a dynamic and a quasi-static part, depending on the radius
$f_{6i,R}$ Factor, considering the percentage of the force on the total damage process, depending on the radius

	f_{61}	f_{62}
Straight track	1,00	0,00
600 m<R<1,000 m	0,80	0,20
400 m<R<600 m	0,70	0,30
250 m<R<400 m	0,60	0,40
R<250 m	0,50	0,50

Consequently, the term is considered in the hybrid TDM by dividing the accumulated damage by the number of axles and multiplying it with the vehicle weight (EQ 7). The marginal cost level of the renewal costs based on gross-tonne-kilometres (evaluated on the calibration lines) is depicted in Figure 82.

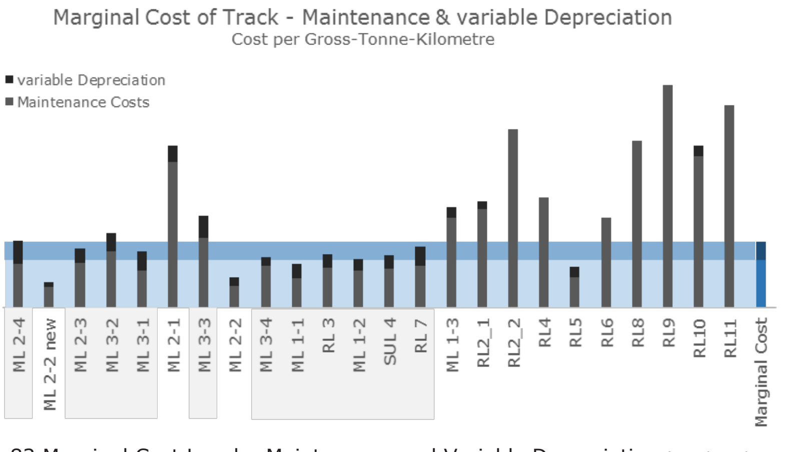

Figure 82 Marginal Cost Level – Maintenance and Variable Depreciation (Track incl. Turnouts)

Considering renewal cost, increases average marginal cost by some 40%. This seems to be reasonable compared to results of econometric models. [74][75]

In a detailed analysis of the calibration lines, all the approaches show high deviations on the high-loaded lines ML 2-3 and ML 3-4 (Table 8).

	gtkm	Swiss TDM	British TDM_{new}	TDM_{Hybrid}
ML 2-4	-19%	-14%	-19%	-14%
ML 2-3	28%	68%	27%	59%
ML 3-2	-2%	-11%	-5%	-10%
ML 3-1	-9%	-9%	-25%	-11%
ML 3-3	-18%	-5%	1%	-3%
ML 3-4	117%	53%	109%	59%
ML 1-1	22%	-11%	6%	-8%
RL 3	37%	38%	36%	21%
ML 1-2	69%	19%	57%	24%
SUL 4	40%	28%	18%	23%
RL 7	-8%	-26%	-1%	-22%
	20%	**17,6%**	**15,1%**	**15,9%**

Table 8 Model Accuracy – Renewal Cost

It becomes apparent that in addition to the loading, the superstructure type influences the cost allocation to a much higher degree compared to the maintenance cost. Furthermore, the superstructure on the lines explains these deviations. Figure 83 shows that these two lines have significantly differing superstructures compared to the other lines: ML 3-4 consists of almost one third of slab track; variable depreciation must be low, accordingly. A superstructure analysis of ML 2-3 demonstrates that the line is only equipped with concrete sleepers, with a significant part being USP sleepers.

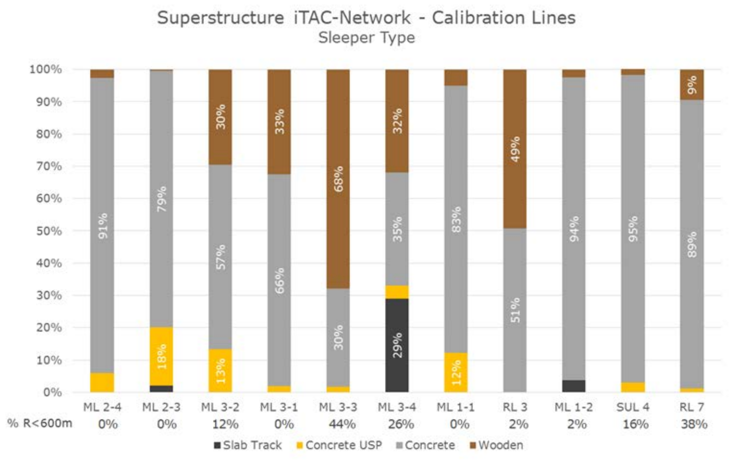

Figure 83 Superstructure Calibration Lines

In both cases, a factor was implemented for all the approaches, reducing the cost recovery by 40%. The result significantly changes the model accuracy (Table 9).

	gtkm	Swiss TDM	British TDM_{new}	TDM_{Hybrid}
ML 2-4	-14%	-8%	-14%	-8%
ML 2-3	-19%	8%	-19%	2%
ML 3-2	4%	-5%	0%	-4%
ML 3-1	-4%	-3%	-21%	-5%
ML 3-3	-13%	2%	6%	4%
ML 3-4	37%	-2%	32%	2%
ML 1-1	29%	-4%	12%	-1%
RL 3	45%	48%	44%	29%
ML 1-2	78%	28%	66%	32%
SUL 4	48%	38%	25%	31%
RL 7	-3%	-20%	5%	-17%
	17%	**7,9%**	**14,1%**	**7,3%**

Table 9 Model Accuracy – Renewal Cost II

The superstructure properties are crucial for all the models. This fact must always be considered.

Applying a turnout factor in the Swiss and hybrid TDM does not significantly increase cost recovery (Table 10). The turnout factor used is much weaker than that for the maintenance cost: Turnouts in curves do not have any significantly differing service lives. In addition, the distribution methodology for the variable depreciation of turnouts may influence the result.

	gtkm	Swiss TDM	British TDM_{new}	TDM_{Hybrid}
ML 2-4	-14%	-8%	-14%	-8%
ML 2-3	-19%	7%	-19%	2%
ML 3-2	4%	2%	0%	4%
ML 3-1	-4%	5%	-21%	3%
ML 3-3	-13%	-1%	6%	0%
ML 3-4	37%	-10%	32%	-6%
ML 1-1	29%	-11%	12%	-8%
RL 3	45%	28%	44%	12%
ML 1-2	78%	21%	66%	25%
SUL 4	48%	52%	25%	44%
RL 7	-3%	-27%	5%	-25%
	17%	**8,0%**	**14,1%**	**7,0%**

Table 10 Model Accuracy – Turnout Factor

The superstructure was analysed beforehand, adding the new line ML 2-2new, the rehabbed line ML 2-2 and the stationary section ML 2-1. According to Figure 84, ML 2-2 should be treated in a similar way to lines ML 2-3 and ML 3-4. The cost recovery factor was therefore set to 60%. For the new line, this is much too low: The line consists of 20% slab track with a perfect substructure in the ballasted part (concrete sleepers). Standard elements assign these tracks extended service lives. A correction factor of 25% was applied for this line segment.

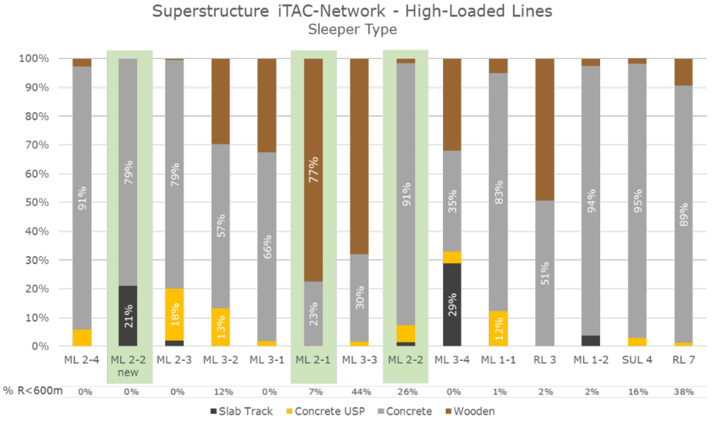

Figure 84 Superstructure for all High-loaded Lines

ML 2-1 does not need any factor, since only variable depreciation of turnouts in the main track is considered. Recovered renewal costs are rather low for this section (Table 11), but the high percentage of wooden tracks and the age of the superstructure mean that a renewal in the near future to decrease the chargeable variable depreciation is necessary.

	gtkm	Swiss TDM	British TDM_{new}	TDM_{Hybrid}
ML 2-4	-14%	-8%	-14%	-8%
ML 2-2 new	-6%	8%	-20%	2%
ML 2-3	-19%	7%	-19%	2%
ML 3-2	4%	2%	0%	4%
ML 3-1	-4%	5%	-21%	3%
ML 2-1	7%	-24%	-33%	-27%
ML 3-3	-13%	-1%	6%	0%
ML 2-2	28%	9%	28%	14%
ML 3-4	37%	-10%	32%	-6%
ML 1-1	29%	-11%	12%	-8%
RL 3	45%	28%	44%	12%
ML 1-2	78%	21%	66%	25%
SUL 4	48%	52%	25%	44%
RL 7	-3%	-27%	5%	-25%
	19%	**8,4%**	**14,1%**	**7,7%**

Table 11 Model Accuracy – Added Lines

For the entire iTAC network, the model accuracy must be low due to the fact that all the models allocate variable renewal costs as a result of transport load. This means that variable depreciation is also considered on lines with low transport volumes, which contradicts the methodology with which the variable depreciation is calculated. On the other hand, maintenance costs on these low-loaded lines are much higher than the marginal cost level. Is was assumed in 3.1.1.1 that this is partly due to the fact that service life is increased excessively on these lines to postpone necessary reinvestment. This fact tends to result in high maintenance, bearing in mind the calculation of the optimal service life. The allocated variable depreciation compensates this to a very low degree. Table 12 provides the model accuracy for all the line segments in the iTAC network. In the red lines with x%, there is an amount of money that has no counterpart, so deviation in % cannot be calculated. Three of four approaches recover more than 100% of the variable depreciation.

	gtkm	Swiss TDM	British TDM_{new}	TDM_{Hybrid}
ML 2-4	-14%	-8%	-14%	-8%
ML 2-2 new	-6%	8%	-20%	2%
ML 2-3	-19%	7%	-19%	2%
ML 3-2	4%	2%	0%	4%
ML 3-1	-4%	5%	-21%	3%
ML 2-1	7%	-24%	-33%	-27%
ML 3-3	-13%	-1%	6%	0%
ML 2-2	36%	9%	28%	14%
ML 3-4	37%	-10%	32%	-6%
ML 1-1	29%	-11%	12%	-8%
RL 3	45%	28%	44%	12%
ML 1-2	78%	21%	66%	25%
SUL 4	48%	52%	25%	44%
RL 7	-3%	-27%	5%	-25%
ML 1-3	91%	164%	82%	15%
RL2_1	139%	7%	72%	-14%
RL2_2	x%	x%	x%	x%
RL4	x%	x%	x%	x%
RL5	87%	6%	74%	11%
RL6	x%	x%	x%	x%
RL8	x%	x%	x%	x%
RL9	x%	x%	x%	x%
RL10	83%	134%	117%	122%
RL11	x%	x%	x%	x%
	111%	**108%**	**98%**	**106%**

Table 12 Model Accuracy – iTAC Network

3.1.3 Summary I – Allocation of Track Costs

When both maintenance and renewal costs are combined at the marginal cost level, and the model accuracy of the different approaches is compared, it becomes apparent that there are relevant differences. The gross-tonne-kilometre approach results in high deviations (Table 13). The low cost recovery on the mountainous line ML 3-3 reaches a maximum, as do the high deviations for lower loaded lines of the calibration set. Note: For the lines ML 2-2 new, ML 2-2, and ML 2-1, adjusting factors have been applied. Without these factors, this approach results in a model accuracy of around only 20%.

	gtkm	Swiss TDM	British TDM_{new}	TDM_{Hybrid}
ML 2-4	0%	-2%	14%	0%
ML 2-2 new	13%	11%	-48%	-1%
ML 2-3	1%	12%	32%	-3%
ML 3-2	-11%	-3%	-27%	-1%
ML 3-1	18%	22%	-22%	13%
ML 2-1	-1%	1%	-76%	-11%
ML 3-3	-27%	-1%	-6%	1%
ML 2-2	18%	-1%	-5%	6%
ML 3-4	18%	-6%	-5%	10%
ML 1-1	52%	-12%	7%	-7%
RL 3	26%	-5%	-5%	-14%
ML 1-2	38%	-14%	6%	-5%
SUL 4	28%	32%	-7%	17%
RL 7	9%	-15%	13%	-7%
ML 1-3	-33%	-4%	18%	-18%
RL2_1	-37%	-45%	-48%	-58%
RL2_2	-63%	-66%	-61%	-74%
RL4	-40%	28%	-18%	1%
RL5	65%	-6%	59%	8%
RL6	-26%	-72%	-41%	-70%
RL8	-60%	-86%	-78%	-89%
RL9	-70%	-93%	-91%	-94%
RL10	-59%	-58%	-48%	-55%
RL11	-67%	-72%	-62%	-73%
∅ Deviation (high-loaded Lines)	**16,7%**	**7,1%**	**19,3%**	**3,7%**
Cost Recovery (Variable Depreciation & Total Maintenance Costs)	**92%**	**90%**	**85%**	**89%**

Table 13 Model Accuracy – Maintenance and Renewal Costs

The British TDM does not work properly for lines with speed levels higher than 160 km/h (ML 2-4, ML 2-2 new, ML 2-3, and ML 3-1). The results obtained at the maintenance level also apply for renewal costs. This is not surprising, since the approach is only valid for speeds of up to 100 mph or 160 km/h, as has been mentioned explicitly . Furthermore, it is not possible to include a turnout factor since there is no specific turnout damage part. This keeps cost recovery low in the lines ML 3-2 and ML 2-1.

Both the Swiss and the hybrid TDMs result in a high degree of accuracy. Of course, this is due to the fact that different factors (turnout factor, new line factor) are applied. This is, however, only possible because the approaches are detailed enough, and because the models work fairly well, including without the factors.

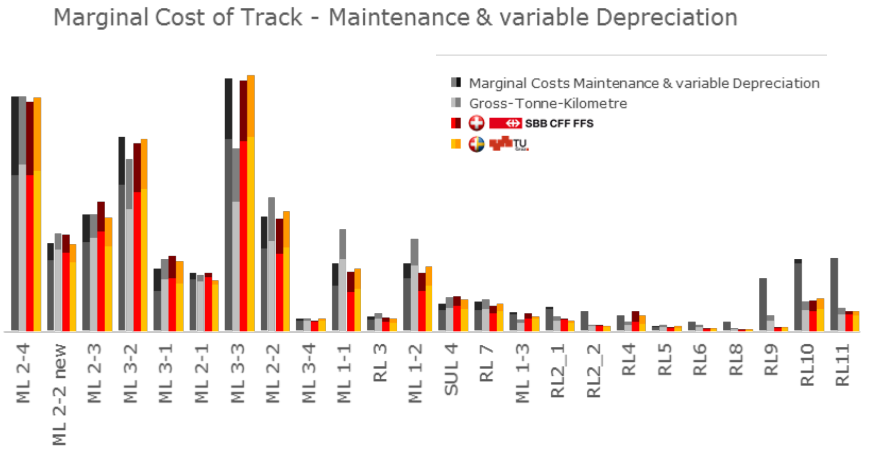

Figure 85 Cost Recovery in the iTAC Network

3.1.4 Infrastructure Demand

The approaches described so far focused on a proper cost allocation. This must be the first goal, considering the marginal cost definition formulated in Regulation 2015/909 [18]. However, the approaches discussed only allocate the existing costs to the users properly. This does not include the question of whether the assets delivering these costs are required by all the users. Directive 2012/34 [7] makes clear that *"the charging … schemes should permit equal and non-discriminatory access for all undertakings and should attempt, as far as possible, to meet the needs of all users and traffic types in a fair and non-discriminatory manner. Such schemes should allow fair competition in the provision of railway services."* and states more precisely: *"charging schemes may need to take account of the fact that different components of the rail infrastructure network may have been designed with different principal users in mind."* The different needs of different TOCs, or rather different market segments, occur in numerous areas of the system. These needs lead to infrastructure investments to a high degree. These aspects are excluded in this chapter as investment costs are irrelevant for the topic of charging.

In terms of direct costs of track, two main issues should definitely be included:

- Higher speeds require a higher degree of precision regarding vertical track geometry. This quality demand automatically leads to higher costs, due to more frequent tamping actions. Although this only effects one maintenance cost position, it is an important and costly one.
- Passenger services demand a higher number of turnouts. Regional trains need to stop more often. To reach the station tracks, turnouts are needed. Long-distance passenger trains require a close crossover distance to keep delays low whenever operational disturbances occur. In addition, turnouts for passenger services are designed for higher speeds. Diverging radii of 500 m or 1,200 m, or even higher, are definitely not installed for freight trains. These longer turnouts necessarily lead to higher costs.

At an average net-wide gross-tonne-kilometre level, these two effects can be summarised quite simply: A passenger traffic gross-tonne-kilometre leads to costs around 30% (long-distance) to 50% (regional) higher than a freight traffic one. This result was achieved by analysing the entire network of the Austrian Federal Railways. [76]

3.1.4.1 Demands due to High Speed Level

Regulation (e.g. ÖBB [77]) foresees different intervention levels for different speed levels. This is true for both Alert Limits (AL) and Immediate Action Limits (IAL). The limit for the longitudinal level of track decreases by 20% for speeds between 120 and 160 km/h compared to the 80 to 120 km/h level. If the speed further increases, the limit drops another 10%.

The intervention limit and tamping cycle are directly proportional (Figure 86). The tamping cycle and tamping costs are indirectly proportional.

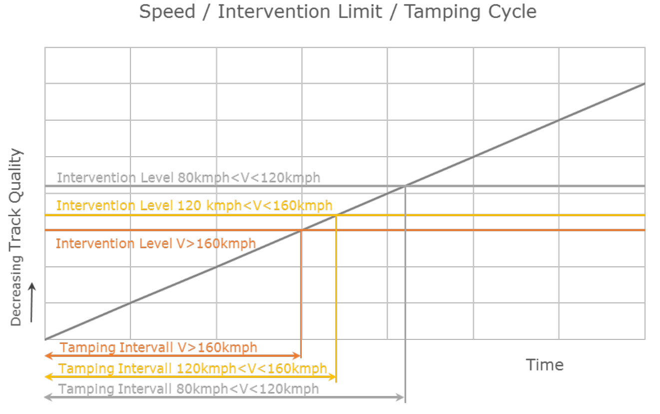

Figure 86 Speed, Intervention Level, and Tamping Cycle

The Swiss TDM approach (and the hybrid one) indirectly cover different costs for different speed levels. Operating with a constant track failure, higher speeds lead to very high dynamic forces. On sections with high line speeds, freight trains are calculated with their maximum permitted speed. This makes it possible to use constant cost calibration factors (k_1). The additional tamping costs due to higher speed levels are covered. The Swedish TDM operates with different track quality levels for different speed levels, but also with constant cost calibration. This delivers unrealistic costs.

The modelling is complex for the gross-tonne approach: The gross-tonnes have to be assessed by factors. These factors vary from line segment to line segment due to different line speeds.

3.1.4.2 Turnout Demand

With a standard design of a double-tracked mainline, the minimum number of turnouts can be assessed: Crossover distance is set to 7.5 kilometres, and the average distance between stations to the same value.

Figure 87 shows that the line configuration (black) is a result of the different needs of different users. Passenger trains require the crossovers to keep delays low in case of operational disturbances. As freight trains are not generally sensible to delays in a minute range, the distance between the crossovers could be much longer; 15 kilometres should be feasible. If a freight train must use a crossover like this, braking and reaccelerating is not at all time-critical. Turnout design could be low-cost; a diverting radius of 300 metres should fit. For regional passenger trains, a 500 m-turnout can be assumed to be the minimum requirement for both crossovers and stationary turnouts. Long-distance passenger trains operated at high speeds demand high-speed turnouts as well. Radii of 1,200 m are assumed; in some cases, even longer turnouts are installed.

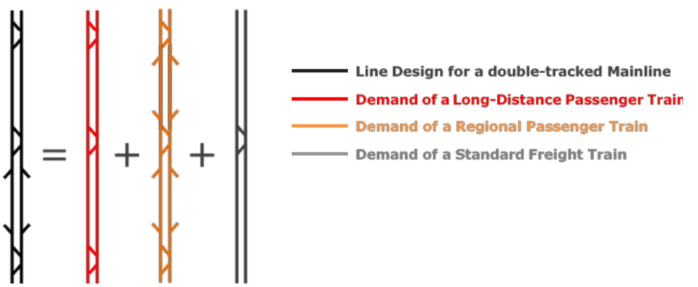

Figure 87 Schematic Line Configuration – Turnouts

Transforming this to values, a long-distance passenger train (LDP) requires 0.27 turnouts per track kilometre. 0.17 turnouts should fit for a standard freight train (F), while a regional passenger train (RP) needs 0.53 turnouts per main track kilometre. Adding the cost factors of the different turnout designs, the spread between high-speed passenger trains and freight trains increases. Table 14 summarises the result.

	LDP	RP	F
1 Crossover/7.5 km	0.27		
1 Crossover/7.5 km plus 2 Stationary Turnouts		0.53	
1 Crossover/15 km			0.13
	R1200 / R500	R500	R300
Cost Impact (R 1,200 m – R 500 m – R 300 m	1.34 / 1.00	1.00	0.89
	LDP	RP	F
Turnout Demand	0.36 / 0.27	0.53	0.12

Table 14 Turnout Demand

Of course, these values can be different for different networks. The importance of the turnout costs definitely requires a demand-based distribution of costs.

For the proposed TDMs, either the Swiss or the hybrid one, it is simple to incorporate this aspect: With special terms for turnouts for maintenance (D5) and variable depreciation (D6), the turnout factors already described can be specified for market segments. In a gross-tonne-kilometre approach, cost allocation keys can be used.

3.1.5 Summary II – Allocation of Track Cost

Demand-specific cost allocation does not increase the cost level, but rather influences the distribution of costs. As the costs for turnouts are notable, demand-based cost allocation is essential.

Principle IV: Demand-based Charging

The specific demand of a train service leads to assets of a certain amount and quality. If the demand is obvious, different charges are already standard (e.g. charges for station use). In mixed-traffic networks, track quality demand and turnout demand differ for different market segments. If this is not taken into consideration in the charging scheme, some trains pay for costs incurred by other trains. This is cross-financing and not in line with the targets of the European Union directives.

The consequences of the demand-based approach are discussed in chapter 0.

3.2 Marginal Cost of Catenary

Principally, the allocation of marginal catenary cost could be based on the track cost allocation. The wear process in the pantograph-overhead wire-contact is similar to the rail-wheel contact.

The cost level is different. Since only overhead wire wear and the consequent costs for exchanging the wire are to be considered in the direct cost, the level is lower than 5%, compared with the direct cost of track. Applying a detailed model might be too much effort considering the output.

Bearing in mind the basic wear principle, the charge should be addressed to the pantograph rather than the train run. A minimum cost-by-cause approach should anticipate charging a train with two locomotives and two pantograph passes twice.

The higher cost level in curves should also be considered. Even though the costs are only 5-10% higher, these costs should be charged.

In the demand-based approach, the speed level is decisive again. For higher speeds, other systems are applied – with higher costs. Using cost allocation keys for trains running at different speeds involves a cost-by-cause issue again.

3.3 Other Marginal Cost

The very basic evaluation in chapter 2.4 indicated that civil structures or other assets do not deliver marginal cost. This is not necessarily the case. As the British estimation of direct cost shows, maintenance of old bridges – namely wooden, brick, and old steel bridges – could be load-dependent to a certain degree. If this is the case, and if it is verifiable by cost accounting, the allocation should be carried out using a wear approach, as the UK does.

Apart from bridges, there might be more cost positions varying with the traffic. For some signalling costs in turnout or on level crossings, this could be the case. Such minor cost positions could be allocated by train-kilometres.

3.4 Summary

A proper cost allocation as the basis for direct cost charging must consist of the following steps:

- Find the costs.
  Costs varying with the traffic load could either be found in analysing engineering data or the cost accounting system. As the costs accounted include various effects, this is very challenging. Engineering knowledge would probably help to extract the marginal cost of infrastructure.
- Understand the cost and its causation.
  It is essential to consider the various impacts on the costs. Evaluating the marginal part of different cost positions requires detailed knowledge of the cost causation.
- Allocate as well as possible.
  When the cost level has been allocated and the cost causing (damage) processes have been understood, a proper cost allocation is required. The allocation must be based on the cost causing mechanisms. These mechanisms vary for different infrastructure properties and for different speeds, and are, of course, effected by the impacting forces.

In chapter 0, only the hybrid TDM is used further, as it has the best model accuracy. The Swiss TDM is close in terms of accuracy, and it is therefore also considered in some analyses. The difference is the higher spread depending on the speed. The British TDM simply does not work properly for speeds higher than 160 km/h, although the accuracy is acceptable. Turnout frequency cannot be specified, hindering a better line-based cost recovery rate and the turnout demand under consideration. The Swedish approach includes an almost unsolvable inconsistency: In the dynamic part of the vertical load, the track irregularities used are different for passenger and freight vehicles. Cost calibration factors must be changed to consider the higher tamping efforts for higher track quality. Furthermore, turnout specification is missing. Simplification and averaging might involve contradictory results or incentives. This is analysed in more detail in chapter 0.

4

Financial Consequences

Introducing such a sophisticated model is not an academic exercise. The changed cost allocation leads directly to financial consequences. These consequences occur at different levels. The main aspects are discussed in the following chapters.

4.1 Financial Consequences at the Level of Market Segments

The proposed methodology shifts costs between the market segments. This is due to the wear-based, speed-dependent allocation, but also due to the line-based and demand-based approach. The analyses provided in this chapter have to be treated cautiously. The shifts from one market segment to the other depend on network properties, speed levels, the vehicles used, and the relative number of trains in the market segments on different lines in the network. All absolute magnitudes are only valid for the iTAC network and traffic, and, of course, for the depicted TDM. The relative shifts are generally true.

Figure 88 shows how the different modulations and TDMs influence the cost allocation in the iTAC network. Generally, it can be summarised that high speed counts and axle load are relevant.

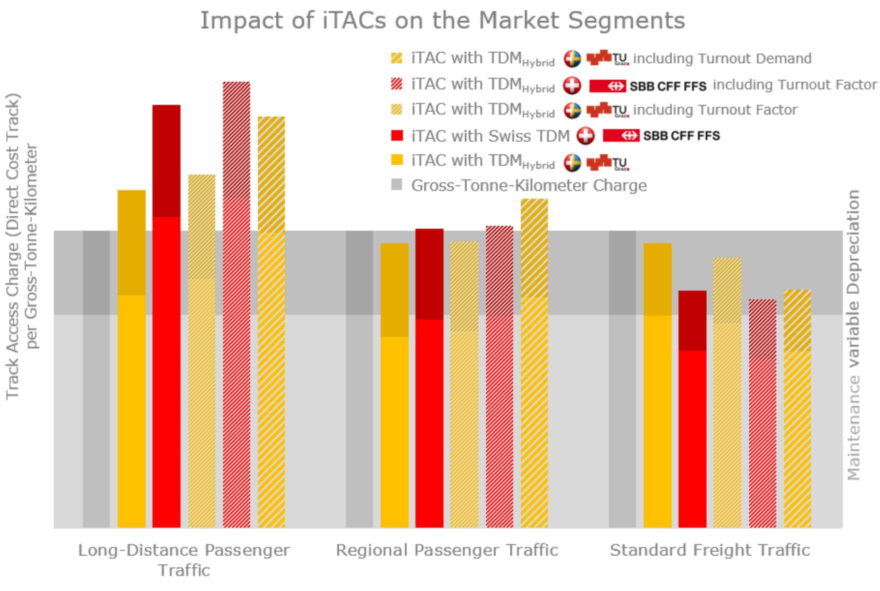

Figure 88 Impact of iTACs on the Market Segments

What is interesting is the increase of costs shifted towards passenger traffic if the turnout factor is applied. This means that wherever passenger trains are operated, there is a higher number or a larger size of turnouts. This general effect is the basis for the turnout demand approach that allocates these costs to the passenger train service. Ultimately, the average gross-tonne-kilometre (this is the unit to which Figure 88 refers) in long-distance passenger traffic is about 80% higher than for a freight train service. Using the Swiss TDM, almost double costs are allocated to the fast, long-distance passenger traffic without the turnout approach.

The higher marginal cost of passenger traffic is nothing new: Econometric models come up with similar results (50 to 150% higher marginal costs for passenger trains [49][78]) using totally different approaches.

Again, these are average network-wide values. In a TDM-based charging scheme the charges change from line to line and for different vehicles. These effects are considered in the following two chapters.

4.2 Financial Consequences at the Level of Railway Undertakings

In brief: Whenever there is only one RU on the network, operating passenger and freight services, no financial consequences occur. Again, the absolute level of charged costs is constant.

With different TOCs on different lines, the strongly spreading charges (Figure 89) might influence the mark-ups.

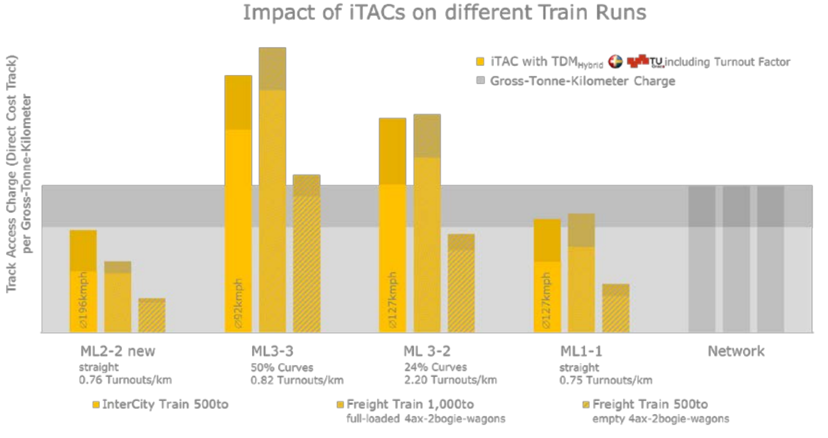

Figure 89 Impact of iTACs on Different Train Runs

RUs operating trains on a very costly, mountainous line very likely face a market situation that can compete with the same mark-up that is set on a similar train operated on a low-cost line. This aspect is relevant for the absolute height of the TACs. To achieve the goals of a wear-based charging scheme, these high differences are important. The high costs of rail wear have a strong leverage effect for incentivising radial steering of the axles. Averaging these costs throughout the network might lead to incentives that are too low. This is discussed in chapter 0 in more detail.

In the Swiss TDM, axles of unloaded freight wagons count. This is easy to see in Figure 90. Of course, multiplying the depicted value (re-referred to gross-tonnes) with wagon weight results in a lower total charge for the empty wagon.

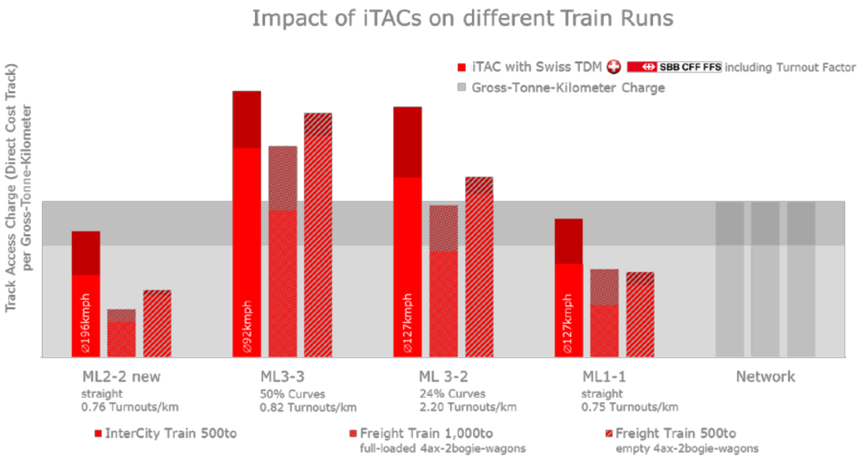

Figure 90 Impact of Swiss TDM-based iTACs on Different Train Runs

As mentioned above, neither the different allocation to market segments nor the different absolute heights on different corridors have a high financial input, as differentiated mark-ups will cap the total charge. What is important is the quality of the vehicles, which is discussed in the following chapter.

4.3 Financial Consequences at the Level of Vehicles

This level is the most relevant one: The total system cost of the railway sector can only be reduced by extracting the entire follow-up costs triggered by the purchase of a new vehicle or trainset. The infrastructure (track) costs play an important role in the calculation of the total cost of ownership, in the business case of the vehicle user (RU) respectively. The infrastructure costs are not by any means the most important cost position in this business case (which is vehicle first cost, of course), but in some cases it might be that these savings achieved are simply missing in decision-making. "Better" vehicles were simply not justifiable in numerous cases as reduced infrastructure costs are not the topic of the RU. As long as reduced track damage and the cost savings achieved are not pushed into the RU's business case by track access charges (this is the only way), track-friendly technology will not break through. This is not theory, but reality. The Shift2Rail lighthouse project R2R deals with exactly this topic in one work-package [79].

To provide at least an idea of what impact iTACs could have on vehicle decisions, three examples are calculated. Note: It is not possible to calculate the entire business case as important data is missing (especially the first cost of the vehicles), but the track cost savings can be highlighted. The three cases analysed are some well-known issues that have been discussed above.

The first example is a cross-anchor bogie for freight wagons. These cross-anchor bogies lead to a radial steering in curves without too much technology involved. This technology is almost as old as the railway system.

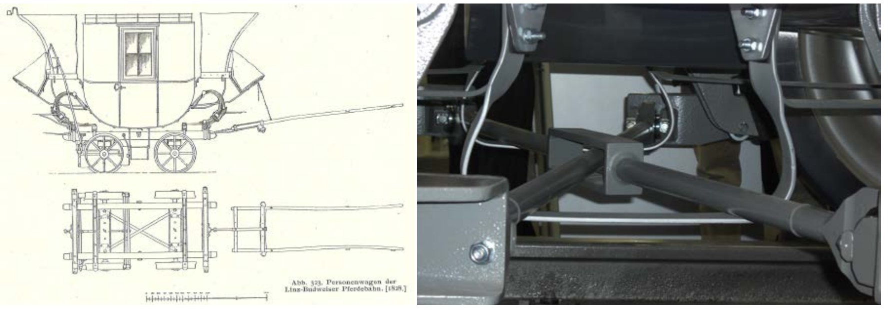

Figure 91 Cross-Anchor Technology back in 1841 [80] and today (TVP2007)

Modern applications exist, but besides some unique cases (South Africa , Viennese Underground, ÖBB freight wagons) have not been put into operation. Monetarising the infrastructure effects, it becomes apparent that this technology is very useful in curved lines.

The example given shows four freight trains on three different line segments:

- A 1,000 to freight train with 10 full-loaded conventional 4ax-Y25-bogie freight wagons on a standard universal 4ax locomotive
- The same freight train with unloaded wagons (~300 t)
- The same 1,000 to freight train but with wagons equipped with cross-anchors (CA)
- This freight train with unloaded wagons

Of course, the cross-anchor technology saves costs in curved lines. The effect is even lower with empty wagons (in the hybrid TDM used). Figure 92 shows the effects recalculated at the gross-tonne level.

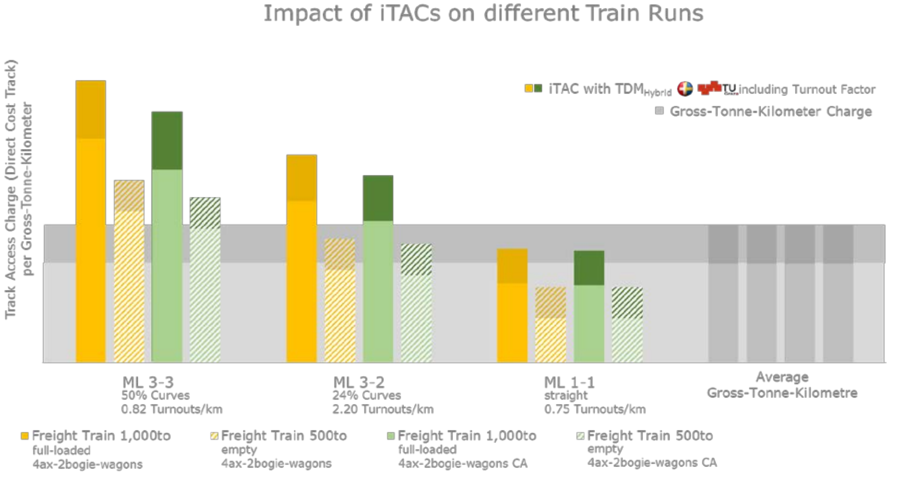

Figure 92 Impact of iTACs on Different Train Runs – Cross-anchor Technology

Whether the difference in marginal track cost pays off in a business case can only be estimated. Assuming 200,000 kilometres per year and wagon, 50-50 loaded and unloaded, and estimating that the wagons run 10% of their total mileage on ML 3-3 characteristics, 10% on ML 3-2 and 80% on straight lines (ML 1-1 characteristic), the additional investment is paid back in around 10 years. Other mission profiles of the wagons and possible additional vehicle maintenance costs may change this value. Anyhow, the business case is not ideal. The amortisation time appears to be quite long. On the one hand, iTACs provide a business case, while average gross-tonne-kilometre charging does not. And on the other hand, amortisation times in the railway business are long, as service lives are long. The same occurs with every new track technology.

The second application analyses the track cost differences for long-distance passenger trains. These trains could be run in a push-pull concept, with a locomotive and standard passenger coaches, or as trainsets. There are many different aspects that could justify one decision or the other, and the example only shows the impact on marginal track cost.

In this case, the trains are analysed at the most detailed level that TDMs deliver: speed classes and radii classes. Trainsets vary widely in terms of technology. The mean cost impact of three different trainsets was therefore calculated. Additionally, there is another topic to be considered: Trains with different lengths and different designs have different weights, a different number of axles and a different number of passenger seats. These differences are eliminated by calculating the track cost per seat kilometre. Figure 93 shows that the difference between the two concepts in terms of track cost is much higher than indicated by the vehicle weight (far right in the figure). Using the hybrid model, the track cost difference per seat kilometre is about doubled compared to the average gross-tonne-kilometre approach.

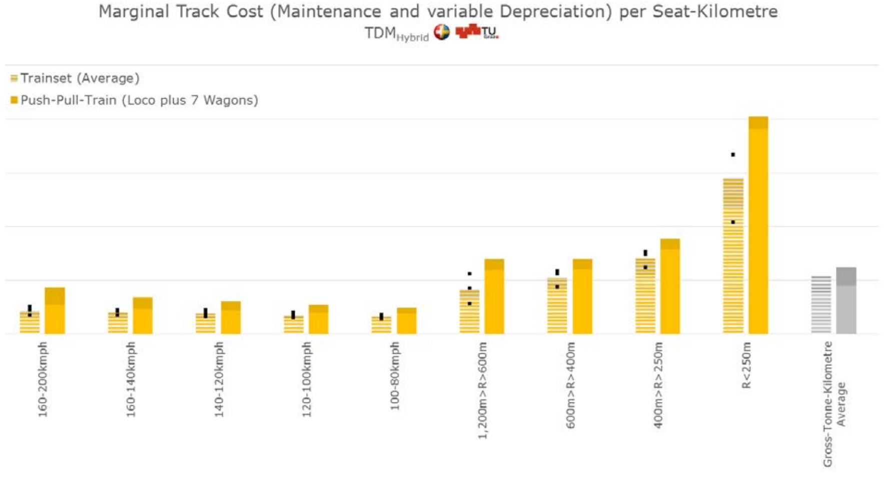

Figure 93 Marginal Track Cost per Seat Kilometre – Push-Pull Train vs Trainset

Figure 93 also indicates that trainset technology differs significantly, especially when it comes to curves. Moreover, considering variable depreciation partly downgrades the advantages of trainsets in curves. In any case, these infrastructure cost differences could be relevant in a decision-making process if they are transferred.

The last example deals with different types of locomotives. The technologies are not described in detail, as the intention is not to go into detail here. It is far more important to highlight that TDMs depict relevant cost differences. In addition, track costs allocated to locomotives are well beyond the average. This is true for all models analysed. An average locomotive gross-tonne-kilometre incurs about double the track cost. This is mostly due to the axle load, unsprung mass, and traction applied.

Figure 94 shows four different locomotives on three different lines. Three of them are 4-axle universal locomotives, and one is a 6-axle freight locomotive. The cost deltas are given per gross-tonne-kilometre; the values must therefore be multiplied by vehicle weight. While the blue vehicle (Loco II) is slightly lighter than the other two 4-axle locomotives, the 6-axle locomotive is naturally about one third heavier. The speed was limited to 140 km/h for all the locomotives, so they always run at the same speed. This is the maximum speed for the six-axle locomotive.

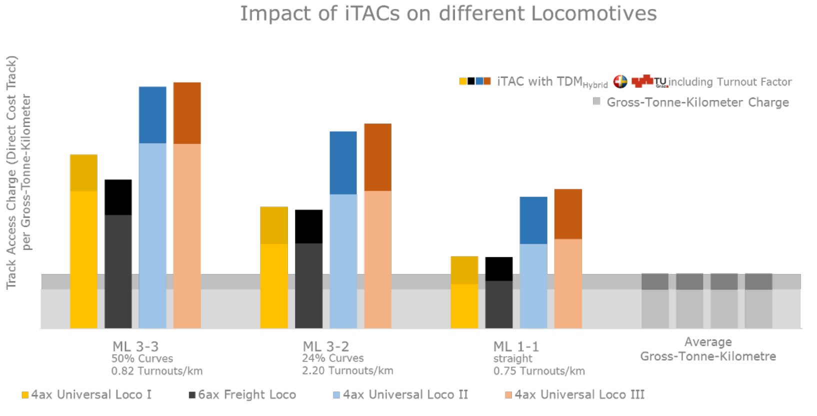

Figure 94 Impact of iTACs on Different Locomotives

Once more, it should be highlighted that all the vehicles analysed are currently charged at the grey level. Despite different effects of the different TDMs analysed, this is certainly wrong.

To summarise, it should be noted that besides any mark-up strategies, the vehicle impact on track cost must be part of any charging system, as support is otherwise provided for wrong and costly decisions. Directive 34/2012 indicates that *"Railway undertakings should receive clear and consistent economic signals from capacity-allocation schemes and from charging schemes which lead them to make rational decisions"* [7]. If the signal is "only weight counts", the system cost will go up. It must be in the IM's best interests to incentivise track-friendly vehicles in order to reduce downtime for maintenance and to provide infrastructure capacity.

4.4 Financial Consequences for the Infrastructure Manager

Apart from the initial migration cost (the model must be set up, calibrated, and put into place), the financial consequences for the IM are low – at least in the short-term. The cost allocation discussed in this paper does not affect the absolute height of the direct cost, but distributes the costs differently. The amount of money charged differs, of course, with changing transport volume, but this also applies for the simple gross-tonne-kilometre approach. If entire fleets are exchanged for low-wear vehicles, the IM might have to make savings that are not achieved in the short term. However, the financial risk for the IM is low, as only cost deltas are relevant. Of course, the same situation occurs for the RU if new vehicles are classified as high-wear ones.

From a mid-term and long-term perspective, the situation changes: If new vehicles on the network are track-friendly, the IM's direct cost income decreases. This is balanced by decreasing track costs. Note: The total income by TACs might be much higher than the direct cost level due to the mark-ups applied. Again, cost deltas are low compared to the total TAC revenues, but relevant in terms of track costs.

Depending on the implementing strategy, the costs for vehicle classification must be covered by either the IM or the RU. These costs are very low for new vehicles, since the vehicle data required can be obtained from standard procedures necessary for vehicle homologation.

It is important to note that the IM is a weak stakeholder in the entire system who might have the lowest interest, as the costs are always covered by either simple gross-tonne-kilometre charges or by public subsidies. On the other hand, one of the IM's major goals is to lower the asset costs and increase the capacity and punctuality by reduced maintenance time.

5 Implementation – as detailed as necessary, as simple as possible

Implementing the direct cost according to Regulation 2015/909 [18] requires a very important, general definition of goals:

- If cost recovery is the only aim, a gross-tonne-kilometre based charge with a detailed analysis of the cost origin is sufficient.
- For defining the best possible cost allocation as a goal, a differentiation of lines is the additional minimum requirement.
- If the aim is to implement an incentive for track-friendly, low-wear vehicles in order to support the general goal of lower system costs, a TDM-based model would be the right choice.

The following chapters only focus on the latter two goals. Implementation strategies naturally require a general agreement between the stakeholders covering the costs of a train run. The IM, RU, regulator, and public authorities are involved and must therefore be informed in as much detail as possible. It is only the public authorities providing substantial financial support for the entire system (infrastructure subsidies and investment, and PSOs) that might be considering the system cost. Both the RU and the IM are focused on their day-to-day business: reducing the costs in their sub-system. The regulator must guarantee that the charging scheme is in line with the legislation and that charges are set in a non-discriminatory way. Without detailed knowledge of cost causation, average gross-tonne-kilometre charges are presumed to discriminate against single users, without knowing which ones. Another approach would be that they are simply wrong, taking the best available understanding of cost causation as a basis. Being able to calculate transparently *"the cost that is directly incurred by a train service"* as it is detailed in this paper changes this point of view.

5.1 Differentiated Gross-Tonne-Kilometre Charges

Based on engineering knowledge and the cost accounting systems, it is possible and feasible to calculate line-specific gross-tonne-kilometre charges. (*"if the infrastructure manager demonstrates … that the values … are significantly different for different parts of its network … the infrastructure manager shall calculate average direct unit costs for the parts of its network …"* [18]) Using engineering models, even demand-specific charges based on gross-tonnes can be calculated. This was carried out for the ÖBB network, taking into account different speed levels and market segment-specific turnout demand, on the one hand, and infrastructure-specific aspects such as track radii distribution and the number of turnouts, on the other. [76]

This strategy delivers a much higher degree of cost recovery accuracy on single lines. Additionally, it partly considers the cost impact of different users. Combined with a cost-neutral bonus-malus system for vehicle quality, this strategy delivers the absolute minimum of today's *"best available understanding of cost causation"* [18].

Many IMs in Europe may lack detailed knowledge and/or – much more relevant – data for a better cost allocation. Vehicle-based charging requires both knowledge and data.

5.2 Vehicle-based Charging

Implementing vehicle-based charges is a challenge, but not particularly difficult technically. As the SBB shows, standard information can be used from the perspective of the infrastructure. If trains are run on railway infrastructure, a great deal of information is transferred from the RU to the IM. In the standard case, this information is stored somewhere and only used for the original task. The same applies for the actual train run operationally. The signalling and control systems, at least, have exact information on which track every single train runs on and which turnout is used. Combining these sources of information and adding the information on track alignment and allowable speed completes the infrastructure data set.

Additionally, it requires every single vehicle to be classified. The SBB formula includes different vehicle properties that can be evaluated through either analytic calculation or multi-body simulation. In the case of a new vehicle entering the network, this data can be provided quite easily and without high additional costs: Vehicle producers use multi-body simulations as standard procedure. However, old vehicles must be classified once. For the IM, the challenge is to store and maintain this vehicle data properly and reliably. Combined with the TDM, the classification provides a set of vehicle prices to be used for the charging.

The charging itself is computer-based, merging infrastructure properties with the vehicle prices. The interface can be designed in a very user-friendly manner by offering a user interface with drop-down menus to define the train run (e.g. from A to B using locomotive C and 20 wagons of type D9). If the user is a freight forwarder rather than a train operator, the information sought might be different, to support the decision on the transport mode rather than the exact train configuration. This can be supported by defining default trains, using either standard vehicles or an average of possible vehicles.

A decision must be made regarding the level of detail for the charging scheme. While Switzerland decided on a fairly detailed system, the UK's curving classes and Austria's "Triebfahrzeugfaktor" (traction unit factor [82][81]) are based on averaged network properties. This is, of course, a complex topic, but has a strong impact on the output: Averaging leads to lower incentives. The damage mechanisms in curves, in particular, are low-weighted, since they are averaged over the network. Even mountainous countries like Switzerland and Austria have railway networks with around 80% tangent tracks or tracks in wide radii.

Regarding the cost-by-cause principle, averaged prices may create unjustifiable results. Defining a standard mission profile for all vehicles (e.g. based on the percentages of radii in the entire network) would lead to a situation in which a high-speed passenger trainset with a stiff design (to be able to handle the high speeds) pays proportionately for tight curves, a line characteristic the train might never face. The same applies vice versa. A curved regional line might require a special trainset for this extraordinary alignment. A steering bogie design would not receive the total monetary effect induced, due to the average price.

A further averaging process concerning the vehicles additionally reduces incentives. The simplest classification into track-friendly and track-harming vehicles treats vehicles equally, which might lead to significant cost differences. The incentive is therefore low, for example in the ÖBB traction unit factor. Another aspect that is even more important from an engineering point of view is how to compare a locomotive with a wagon. It is technically impossible to compare vehicles of different vehicle classes. A very simple vehicle-based charging scheme for the entire vehicle fleet ("good and bad") is not target-oriented and technically unjustifiable.

All these issues must be considered in the implementation process. The Swiss approach shows that challenges can be overcome.

5.3 iTACs

Adding additional information in order to achieve a more appropriate cost recovery on discrete line segments is not a great challenge compared to the vehicle-based approach. Turnout factors can be easily calculated, as data is available (number and size of turnouts in different line segments). The same applies for extraordinary superstructure properties (slab tracks, new lines).

In terms of rail regulation, iTACs support legal security: A high accuracy of cost recovery by iTACs provides results easily surveyed by the regulator. Line-based charges and costs fit. A sound and detailed cost accounting system supports this, of course. The iTAC methodology guarantees that no costs are shifted between lines of the network and therefore ensures that RUs only pay for what they are responsible for through running their trains.

Next to the state-of-the-art cost allocation based on the best available understanding of cost causation, vehicle-based charges provide an incentive for high-quality vehicles, supporting the goal of decreased system costs.

The demand-based approach – in this paper analysed in detail for the turnout demand – takes into account the fact that different users of a mixed-traffic network have different demands. This is particularly important for Europe's rail-bound freight traffic. Freight transportation does not trigger the infrastructure costs, bearing in mind low-cost rail freight operation in the USA or elsewhere.

6
Further Charging Aspects

There are some topics that are supposed to be treated within the "cost that is directly incurred by a train service" mentioned in Directive 34/2012 [7]. Congestion or scarcity of capacity are doubtlessly important aspects. Track access charging is definitely the proper tool to provide incentives. However, both aspects do not influence the direct cost. This might be the case to a very low degree, as track closures are short in overcrowded line segments and track work is more likely to be carried out during night or weekend shifts. Although both aspects lead to higher track costs (chapter 2.2.6), it is challenging to determine these effects. If the intention of the Directive is to shift traffic away from peak hours, this is an operational question rather than a cost topic. Further incentives are discussed once more in chapter 6.2. Although mark-ups are not the focus of this paper, some comments must made, as direct costs and mark-ups are not entirely independent from each other.

6.1 Mark-ups

As has already been stated several times, mark-ups are an economic issue that is better not touched upon by engineers. An estimation of *"what the market can bear"* is doubtlessly challenging. Determining differentiated direct costs does not make it easier. If a definition is provided of how much single market segments can contribute to cover fixed infrastructure costs, the differentiated direct costs presented in this paper must be considered. Train operating companies that need to use costly corridors (especially mountainous lines) will have to be capped by lower mark-ups in order to be competitive. Even though total TACs are equalised in this way, full cost transparency and – most importantly – incentives for higher vehicle technology are preserved for the full amount.

Generally, mark-ups are a mirror for the state's willingness to cover the infrastructure costs of railways. Charging at the marginal cost level is only currently carried out in Sweden (where TACs might even be below the marginal cost). On the other hand, it should be in the state's interests to provide the infrastructure at marketable charges. While freight traffic is in strong competition with road transport, rail passenger traffic might not be. Long-distance passenger trains compete with aviation rather than with road transport. Intercity services are competitive if they are fast and punctual; and even if ticket prices influence the choice of transport mode, they are not triggered by TACs, which are only one cost position in the RUs' total cost.

A very different situation occurs in regional and suburban rail passenger traffic. These modes of transport are subsidised by public authorities in most countries. Whether Member States put money into PSOs, allowing higher track access charges, or move the money to the IM, supporting low TACs, is a political decision. Both possibilities are apparent in Europe (Figure 19).

6.2 Incentives

6.2.1 Performance Scheme/Slot Quality

Directive 34/2012 foresees a mandatory performance scheme to incentivise both IM and RUs to reduce downtime. The reciprocal payment of fines, which takes place in some countries, is a possible approach, but may not be very target-oriented. From the IM's perspective, it would be much more intelligent to sell slots with different qualities. In this case, a certain degree of punctuality or a maximum number of delay minutes would be offered.

This defines a strong incentive to the IM to optimise its maintenance scheme. Premium or high-quality train slots for delay-sensible trains should not be bothered by any maintenance-related hindrances, while low-quality slots allow for flexibility.

The spread between high-quality and low-quality slots could be based on the costs of operational hindrances at the RUs. The relation between track closure and track work cost is well known and could be used for this case (chapter 2.2.6).

The procedural method and consequences have been analysed in a study for the Austrian Federal Railways [76].

6.2.2 Congestion / Scarcity

Congestion and capacity scarcity are similar phenomena. While the first is based on the variable amount of traffic in the daily records, the second requires infrastructure measures to be solved. Delays may occur in both cases due to strict, tight timetables lacking sufficient time reserves.

In this case, the use of operational hindrances costs could also be a sound basis for a cost-related incentive.

6.2.3 Noise Differentiation

Directive 34/2012 explicitly addresses charges or incentives supporting the retrofitting of freight wagons. Noise is not only a freight transport issue. In the Netherlands, the frequency of passenger trains is the crucial topic (freight transport has a very low modal split share in Holland). Low-noise vehicle designs will be in demand in the near future far beyond the level of K- or LL-brakes of freight wagons. A simple bonus for low-noise technology would be sufficient in a TAC scheme, without doubt. In this case, the Member States would finance the technology. IMs do not have money for any incentives; they cover a certain part of their costs by TACs and receive the rest from public subsidies (this is also true for e.g. an ETCS incentive). Moreover, Swiss experiences showed that in addition, the initial cost of the retrofit also needs subsidisation.

For the TACs, it would be much more favourable to establish a neutral bonus-malus-system based on a cost approach. While the latter defines the cost spread, the neutral bonus-malus generates an increasing incentive: In the beginning, a high bonus to few low-noise vehicles is paid by a rather low malus of many loud vehicles – the incentive to invest in low-noise technology is high. If the proportions change, the bonus decreases, but the malus increases – a strong incentive to get rid of the old technology.

A cost-based approach for noise-differentiated charges for freight trains exists [82]. This approach is also feasible for passenger trains. Analysing line capacities and vehicle data again is a precondition for the implementation.

6.3 Summary

Mark-ups are open to many approaches. Of course, the financial load that can be covered by a market segment is ultimately the most relevant trigger of the cap. In addition to the operational aspect discussed and the topic of noise, other issues of today's railway system are to be either covered by mark-ups or treated with separate incentives. Alternative routing, CO_2 emissions, accidents, the use of diesel on electrified lines, and the ETCS bonus (which must be guaranteed by legislation) are just a few of the other aspects. Continuous improvement of incentives and a wise adjustment of mark-ups will be a work in progress and part of a process of system optimisation.

7
Summary and Outlook

A great deal of knowledge and data is required to establish cost allocation as presented in this paper. Ultimately, it is still a challenging task to put it in place. So far, many models have been created that are still awaiting implementation. In the railway sector, innovation is often not implemented, as it cannot be assured that it delivers absolute truth. In the topic considered, this is even more relevant, since it is also a juridical objective.

The models discussed in this paper have different sources and different levels of objectiveness. While the costs defined by infrastructure properties are fairly easy to prove (e.g. higher costs in smaller radii), the track deterioration models based on vehicle-track interaction are not. On the other hand, it is not always about absolute truth. The models analysed deliver strongly differing results when it comes to the differentiation of the influences of speed and axle load. In this area, there is doubtlessly a need for further research. However, all the models provide similar "best guesses": Higher axle load leads to higher cost; more turnouts are followed by higher expenditure; higher speeds do not come free of charge; a sustainable, high-quality track decreases maintenance demands, and many more. All these "guesses" can be supposed to be true, based on the best understanding available today, and not vice versa. In today's charging practice, higher axle loads, higher speeds, more turnouts, or better track superstructure are supposed to lead to equal costs. Without doubt, that is simply wrong. In addition, this point of view provides the wrong economic signals.

The infrastructure manager is supposed to *"… reduce the level of access charges and the costs of providing infrastructure."* [7] In day-to-day asset management, the reduction of life cycle costs is the highest goal. A sustainable infrastructure will deliver the lowest long-term cost. The IM should incorporate the aim to reduce the loading through innovative, track-friendly vehicle technology. A vehicle-based charging scheme is therefore essential.

Legislation is often blamed for hindering innovation. This is certainly not the case for highly sophisticated charging schemes. *"Methods for apportioning costs established by infrastructure managers should be based on the best available understanding of cost causation and should apportion costs to the different services offered to railway undertakings and, where relevant, to types of rail vehicles."* [18] This is relevant, as evaluations in this paper and elsewhere show.

It requires courage, will, and commitment to innovation to establish intelligent and transparent charges. All stakeholders in the system should try to overcome the organisational interfaces, to work together on a competitive transport mode. Of course, such charges are complex. Just because the new and better method is complex does not mean that the existing, simple one should remain. In the topic of charging, in particular, the time has come for railways to forget the idea that everything can be viewed on a sheet of paper and calculated on another one. Today's possibilities of computer-aided processes provide support for even a complex calculation to be handled simply. Very flexible ticket pricing in passenger traffic might be a great innovation for railway's infrastructure managers: Passengers do not calculate their train fares by hand, but simply enter their destination into the system and receive the best or the available price.

The UK took the first step towards detailed track access charging. Austria can probably be credited with the earliest implementation of a vehicle-based incentive, using the "Triebfahrzeugfaktor" [81]. Switzerland will provide a great incentive with its state-of-the-art charging scheme using the "Verschleissfaktor" in 2017 [59]. The SBB wear factor covers vehicle characteristics as well as infrastructure properties. Feedback from vehicle producers is positive and shows potential savings. [83][84] The charging will be based on the actual run of a train, considering speed level and track radius. Possible further improvements are provided in this paper.

More detailed knowledge about wear processes is definitely required. An appeal is made to researchers, infrastructure and vehicle engineers to expand the knowledge currently available and to modify and improve track (and vehicle) deterioration models. The task for the entire system is to find new solutions for tracks and vehicles at affordable costs. In the end, competitiveness with other modes counts.

If liberalisation of the European railway sector leads to a better system (perhaps in the future, since it has so far created more trouble than benefits), it will be because the sector has learned to live with this concept. Track access charges are one of the key issues to be considered.

References

[1] Commission of the European Communities: *White Paper, European transport policy for 20120: time to decide*, Brussels (Belgium), 12.9.2001

[2] Council of the European Communities: *Council Directive of 29 July 1991 on the development of the Community's railways (91/440/EEC)*, Brussels (Belgium), 24.08.1991

[3] Council of the European Union: *Council Directive 95/19/EC of 19 June 1995 on the allocation of railway infrastructure capacity and the charging of infrastructure fees*, Brussels (Belgium), 27.06.1995

[4] European Parliament and Council of the European Union: *Directive 2001/12/EC of the European Parliament and the Council of the European Union of 26 February 2001 amending Council Directive 91/440/EEC on the development of the Community's railways*, Brussels (Belgium), 15.03.2001

[5] European Parliament and Council of the European Union: *Directive 2001/13/EC of the European Parliament and the Council of the European Union of 26 February 2001 amending Council Directive 95/18/EC on the licensing of railway undertakings*, Brussels (Belgium), 15.03.2001

[6] European Parliament and Council of the European Union: *Directive 2001/14/EC of the European Parliament and the Council of the European Union of 26 February 2001 on the allocation of railway infrastructure capacity and the levying of charges for the use of railway infrastructure and safety certification*, Brussels (Belgium), 15.03.2001

[7] European Parliament and Council of the European Union: Directive 2012/34/EU of the European Parliament and the Council of the European Union of 21 November 2012 establishing a single European railway area (recast), Brussels (Belgium), 14.12.2012

[8] Finger, M.; Putallaz, Y., Van de Velde, D.: *Solid infrastructure financing for an efficient rail system*, Brussels (Belgium), 2015

[9] IBM Business Consulting Services: *Liberalisierungsindex Bahn 2002 - Vergleich der Marktöffnung in den Eisenbahnmärkten der 15 Mitgliedsstaaten der Europäischen Union, der Schweiz und Norwegens*, Berlin (Germany), 20.01.2003 (German only)

[10] IBM Business Consulting Services: *Liberalisierungsindex Bahn 2004 - Vergleich der Marktöffnung der Eisenbahnmärkte der 15 Mitgliedsstaaten der Europäischen Union, der Schweiz und Norwegens*, Berlin (Germany), 10.05.2004 (German only)

[11] IBM Business Consulting Services: *Liberalisierungsindex Bahn 2007 - Marktöffnung: Eisenbahnmärkte der Mitgliedstaaten der Europäischen Union, der Schweiz und Norwegens im Vergleich*, Brussels (Belgium), 17.10.2007 (German only)

[12] IBM Business Consulting Services: *Rail Liberalisation Index 2011 - Market opening: comparison of the rail markets of the Member States of the European Union, Switzerland and Norway*, Brussels (Belgium), 20.04.2011

[13] Boston Consulting Group: *The 2012 European Railway Performance Index - Understanding What Drives High Performance*, 11.2012

[14] Boston Consulting Group: *The 2015 European Railway Performance Index Exploring the Link Between Performance and Public Cost*, 03.2015

[15] European Railway Agency: *Railway Safety Performance in the European Union 2014*, Valenciennes (France), 2014

[16] European Commission: *Report from the Commission to the Council and the European Parliament – Fourth report on monitoring development of the rail market COM(2014) 353*, Brussels (Belgium), 13.06.2014

[17] European Commission: *Commission staff working document accompanying the document Fourth report on monitoring development of the rail market COM(2014) 353*, Brussels (Belgium), 13.06.2014

[18] European Commission: Commission implementing Regulation (EU) 2015/909 of 12 June 2015 on the modalities for the calculation of the cost that is directly incurred as a result of operating the train service, Brussels (Belgium), 13.06.2015

[19] Independent Regulators' Group - Rail: *Updated review of charging practices for the minimum access package in Europe*, Warsaw (Poland), 11/12.11.2015

[20] European Commission: EU transport in figures – statistical pocketbook 2015, Brussels (Belgium), 2015

[21] International Union of Railways (UIC): *Lasting Infrastructure Cost Benchmarking LICB – 15 years of Benchmarking 1996-2010*, Paris (France), September 2013

[22] International Union of Railways (UIC): *Lasting Infrastructure Cost Benchmarking (LICB) – 10-years of Benchmarking 1995-2005*, Paris (France), September 2007

[23] Stalder, O. (SBB/UIC): *International benchmarking of track cost*, Proceedings of the AREMA 2001 annual conferences, Chicago (US), 09-12.09.2001

[24] Bente, H.; Kindler, T., Wittmeier, K. (BSL Management Consultants): *Network Rail: Rail Infrastructure Cost Benchmarking, Final Report*, Hamburg/London (UK), 01.04.2008

[25] Smith, A.; Wheat, P. (Institute for Transport Studies); Nixon, H. (ORR): *International benchmarking of Network Rail's maintenance and renewals costs*, London (UK), 06.2008

[26] Marschnig, S.; Veit, P.: *Optimierte Einheitskosten - Sperrpausendauer und Baustellenlänge*, ZEVrail, 134 (2008) 10, Berlin (Germany), 2008 (German only)

[27] Veit, P.: *Infrastructure maintenance strategies*, rail international, Brussels (Belgium), 06.2002

[28] Veit, P.; Wogowitsch, M.: *Track Maintenance based on life-cycle cost calculations*, Prom@in-Fraubhofer Institut IITB, Karlsruhe (Germany), 11.2002 (German only)

[29] Veit, P.: *Wirtschaftliche Bewertung von Strategien im Bereich Fahrweg*, ETR Eisenbahntechnische Rundschau 5/2000, Darmstadt (Germany), 05.2000 (German only)

[30] Renggli, R.; Holzfeind, J.; Marschnig, S.: *Netzweite Investitions- und Instandhaltungsstrategien im Bereich Fahrbahnoberbau der SBB*, ETR Eisenbahntechnische Rundschau 6/2012, Darmstadt (Germany), 06.2012 (German only)

[31] Veit, P.; Marschnig, S.: *Strategie Komponenten Schiene*, Projektbericht ÖBB, Graz (Austria), 2005 (German only) UNPLUBLISHED

[32] Veit, P.; Marschnig, S.: *LCC Gleise Aktualisierung*, Final Report OeBB, Graz (Austria), 2010 (German only) UNPLUBLISHED

[33] Veit, P.; Marschnig, S.: *Strategie Komponenten Weichen*, Final Report OeBB, Graz (Austria), 2005 (German only) UNPLUBLISHED

[34] Veit, P.; Marschnig, S.; Enzi, M.; Neuper, G.: *LCC Weichen Fahrweg Aktualisierung 2013*, Final Report OeBB, Graz (Austria), 2013 (German only) UNPLUBLISHED

[35] Veit, P.; Marschnig, St.: *LCC Weichenheizung – Systementscheid*, Final Report OeBB, Graz (Austria), 2008 (German only) UNPLUBLISHED

[36] Veit, P.; Marschnig, S*.: LCC Weichen unter Berücksichtigung signaltechnischer Komponenten – Systementscheid*, Final Report OeBB, Graz (Austria), 2010 (German only) UNPLUBLISHED

[37] Veit, P.; Marschnig, S.: *LCC Oberleitungen*, Final Report OeBB, Graz (Austria), 2007 (German only) UNPLUBLISHED

[38] Veit, P.; Marschnig, S.; Bauer, M.; Enzi, M.: *LCC Oberleitungen Komponenten*, Final Report OeBB, Graz (Austria), 2015 (German only) UNPLUBLISHED

[39] Veit, P.; Marschnig, S.: *LCC Brücken – Aktualisierung*, Final Report OeBB, Graz (Austria), 2009 (German only) UNPLUBLISHED

[40] Veit, P.; Marschnig, S.: *LCC Eisenbahnkreuzungen – Systementscheid*, Final Report OeBB, Graz (Austria), 2010 (German only) UNPLUBLISHED

[41] Veit, P.; Marschnig, S.: *LCC Bahnsteige – Systementscheid*, Final Report OeBB, Graz (Austria), 2009 (German only) UNPLUBLISHED

[42] Veit, P.; Marschnig, S.: *LCC Lärmschutzwände – Systementscheid*, Final Report OeBB, Graz (Austria), 2010 (German only) UNPLUBLISHED

[43] Veit, P.; Marschnig, S.: *Standardelemente Gleise und Weichen*, Final Report SBB, Graz (Austria), 2014 (German only) UNPLUBLISHED

[44] Veit, P.; Marschnig, S.: *Investment and Maintenance Strategies Track*, Final Report HŽ, Graz, 2006 (German only) UNPLUBLISHED

[45] Veit, P.; Marschnig, S.: *Investment and Maintenance Strategies Turnouts*, Final Report HŽ, Graz (Austria), 2008 (German only) UNPLUBLISHED

[46] Ekberg, A.; Paulsson, B.: *INNOTRACK Concluding Technical Report*, Paris (France), 2010

[47] Network Rail: *Periodic Review 2013 – Conclusions on the allocation of the Variable Usage Charge*, London (United Kingdom), April 2013

[48] Munduch, G. et al.: *Estimating Marginal Costs for the Austrian Railway System*, Vienna (Austria), 2002

[49] Andersson, M.: *Marginal cost of railway infrastructure wear and tear for freight and passenger trains in Sweden*, Borlänge (Sweden), 2011

[50] International Union of Railways (UIC): *UIC Code 714 E – Classification of lines for the purpose of track maintenance*, Paris (France), 2009

[51] Calvo, F. et al.: *Rail track costs management for efficient railway charges*, Proceedings of the Institution of Civil Engineers, London (United Kingdom), 2011

[52] Safety & Standards Directorate Railtrack PLC: *Track Standards Manual - Section 1: Basic Track Category Matrix*, London (United Kingdom), 1995

[53] Group Standards Railway Technical Centre: *Group Standard GM/TT0088 Permissible Track Forces for Railway Vehicles*, Derby (United Kingdom), 1993

[54] ORE: *D 161.1 RP4 The Dynamic Effects due to Increasing Axle Loads from 20 to 22.5 t*, Utrecht (Netherlands), 1987

[55] Burstow, M.: *Whole Life Rail Model Application and Development for RSSB – Continued Development of an RCF Damage Parameter*, Derby (United Kingdom), 2004

[56] Burstow, M.: *V/T SIC Annual Seminar: What we now know*, London (United Kingdom), 04.11.2009

[57] Whitney, B.: *Rail Management Update*, London (United Kingdom), 26.10.2011

[58] Nerlich, I.; Holzfeind, J.: *Wie wirtschaftlich ist gleisschonendes Rollmaterial … wie einen Verkehr von morgen in der zukünftigen Auswirkung auf Gleisinstandhaltungen beziffern?*, ZEVrail 138 (2014) Tagungsband Graz 2014, Berlin (Germany), 2014 (German only)

[59] Holzfeind, J.; Nerlich, I.; Giger, M.; Marschnig, S.: *Verschleißabhängige Komponente im Trassenpreissystem der Schweiz – ein Anreiz zur Rückbessinnung auf ein Gesamtoptimum*, ZEVrail 139 (2015) 6-7, Berlin (Germany), 2015 (German only)

[60] Marschnig, S.; Holzfeind, J.: *Verursachungsgerechte Kostenzuordnung der Fahrbahnerhaltungsarbeiten am Beispiel des Verschleißmodells der SBB*, ZEVrail 137 (2013) Tagungsband SFT Graz 2013, Berlin (Germany), 2013 (German only)

[61] Öberg, J.; Andersson, E.: *Determining Deterioration Cost for Railway Tracks*, Proceedings IHHA Kiruna, Virginia Beach (United States), 2007

[62] Andersson, E.; Öberg, J.: *Track access charging with respect to vehicle characteristics - Track access charging with respect to vehicle characteristics Second Edition*, Borlänge (Sweden), 2007 UNPUBLISHED

[63] Öberg, J.; Andersson, E.: *Determining the deterioration cost for railway tracks*, Proc. IMechE Vol. 223 Part F: J. Rail and Rapid Transit, London (United Kingdom), 2007

[64] Worley, B.; Burstow, M.: *The Variable Usage Charge (VUC) in CP5*, London (United Kingdom), 2014

[65] Serco Commercial: *VTISM Analysis to Inform the Allocation of Variable Usage Costs to Individual Vehicles*, Cheshire (united Kingdom), 2013

[66] Veit, P.; Marschnig, S.: *Expected tamping demand for HS2 conditions*, Final Report HS2, Graz (Austria), 2015 UNPUBLISHED

[67] Hummitzsch, R*.: Zur Prognostizierbarkeit des Qualitätsverhaltens von Gleisen - Statistische Analyse des Gleisverhaltens zur Erstellung eines Prognosemodells*, PhD Thesis, Graz, 2009 (German only)

[68] Hansmann, F.: Innovative Messdatenanalyse – ein Beitrag für ein nachhaltiges Anlagenmanagement Gleis, Dissertation, Graz (Austria), 2015 (German only)

[69] Audley, M.; Andrews, JD.: *The effects of tamping on railway track geometry degradation*, Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit 2013, London (United Kingdom), 2013

[70] INNOTRACK: D1.3.6 The state of the art of the simulation of vehicle track interaction as a method for determining track degradation rates Part 2 – High Resolution models and the level of validation generally, Brussels (Belgium), 2006

[71] Holzfeind, J.; Hummitzsch, R.: *Qualitätsverhalten von Gleisen*, ZEVrail, 132 (2008) 6-7, Berlin (Germany), 2008 (German only)

[72] Redtenbacher, M.: *Realisierte Gleisliegedauern im ÖBB-Netz*, Master Thesis, Graz University of Technology, Graz (Austria), 2013 (German only)

[73] Jörg, A.: *Ermüdungsfestigkeit von Eisenbahnschienen*, Master Thesis, Graz University of Technology, Graz (Austria), 2004 (German only)

[74] Andersson, M.; Smith, A.; Wikberg, A.; Wheat, P.: *Estimating the marginal cost of railway track renewals using corner solution models*, Transportation Research Part A: Policy and Practice Volume 46 Issue 6, Oxford (United Kingdom), July 2012

[75] Andersson, M.: *Empirical essays on railway infrastructure costs in Sweden*, PhD Thesis, Royal Institute of Technology, VTI – Swedish Road and Transport Research Institute, Stockholm/Borlänge (Sweden), 2007

[76] Marschnig, S.: *Verursachungsgerechte Kostenzuscheidung für die Trassennutzung*, Final Report OeBB, Graz (Austria), 2013 (German only) UNPUBLISHED

[77] OeBB: *Instandhaltungsplan Oberbauanlagen*, Vienna (Austria), 01.09.2014 (German only) UNPUBLISHED

[78] CATRIN: *D8 – Rail Cost Allocation for Europe Annex 1B – Track maintenance and renewal costs in Switzerland*, Brussels (Belgium), 2009

[79] Peris, E.; Goikoetxea, J.: *Roll2Rail Developing the rolling stock of the future*, European Railway Review Volume 21 Issue 5, Kent (United Kingdom), 2015

[80] Strach, H.: *Geschichte der Eisenbahnen der oesterreichisch-ungarischen Monarchie – Band II*, Vienna (Austria), 1898 (German only)

[81] Marschnig, S.: *Fahrzeugkonzeption und Gleisverschleiß – ÖBB-Triebfahrzeugfaktor*, Elektrische Bahnen 6/2012, Munich (Germany), 2012 (German only)

[82] Marschnig, S.: *Qualitätsfaktor Lärm als Teil des Infrastrukturbenützungsentgeltes*, PhD Thesis, Graz University of Technology, Graz (Austria), 2007 (German only)

[83] Schneider, R.: *Neues, verschleißabhängiges Trassenpreismodell in der Schweiz – Möglichkeiten aus Seiten des Fahrzeugs*, 139 (2015) 6-7, Berlin (Germany), 2015

[84] Strommer, K.: Verschleißabhängige Trassenpreise – Chance für Innovation oder Risiko der Komplexitätserhöhung, ZEVrail, 139 (2015) 6-7, Berlin (Germany), 2015

Annex – The iTAC Network

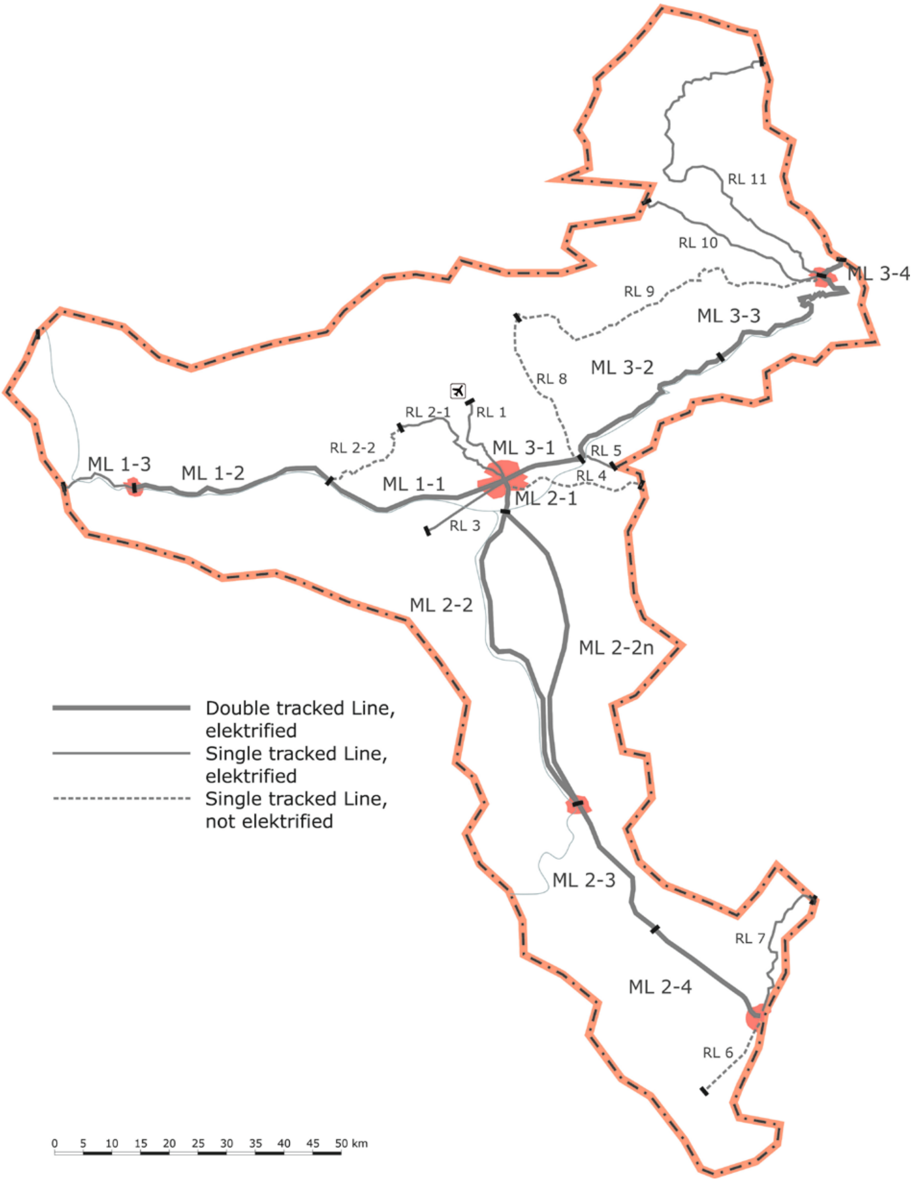

Figure 95 The iTAC Network

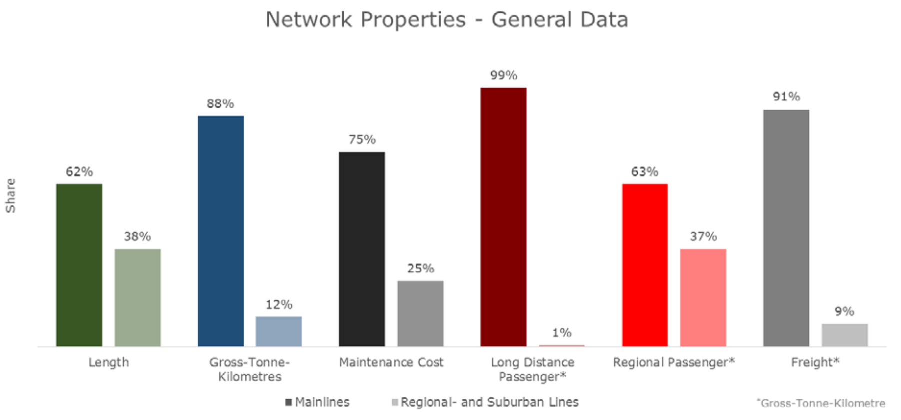

Figure 96 Network Properties - General Data

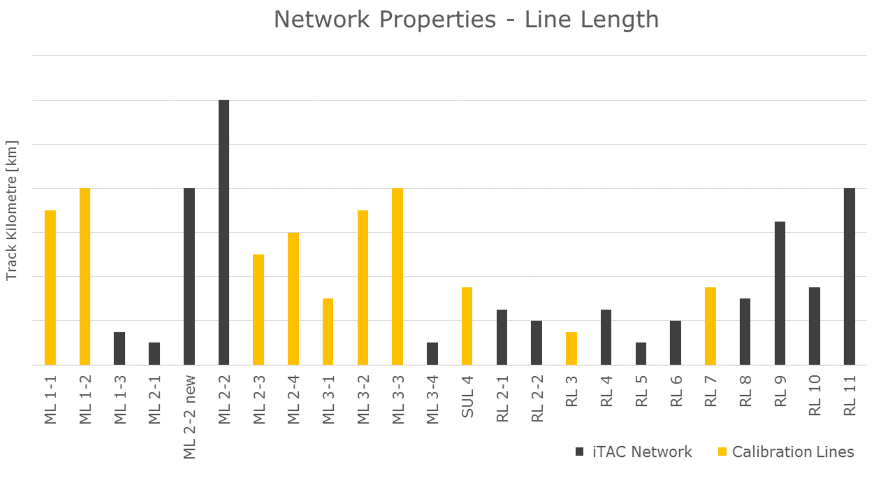

Figure 97 Network Properties - Line Length

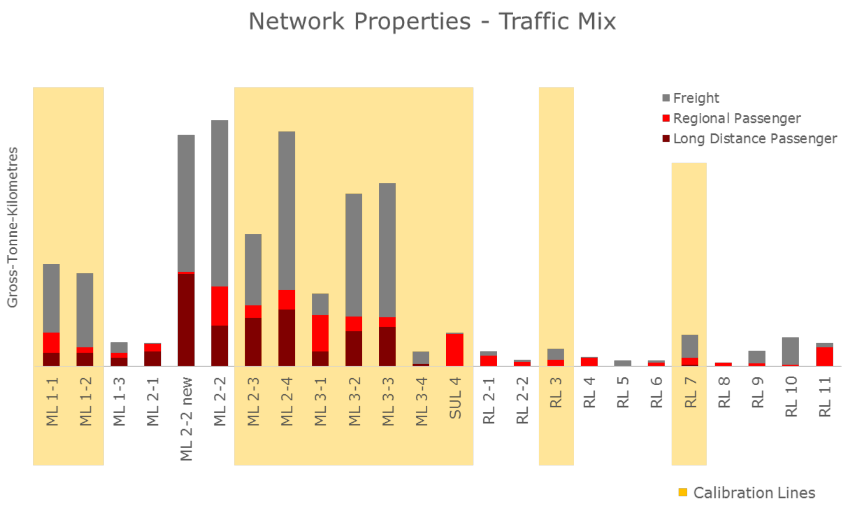

Figure 98 Network Properties - Traffic Mix

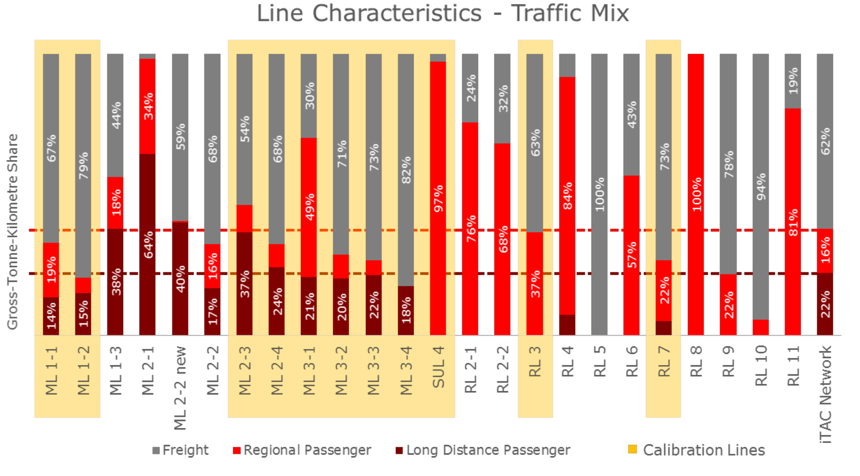

Figure 99 Line Characteristics - Traffic Mix

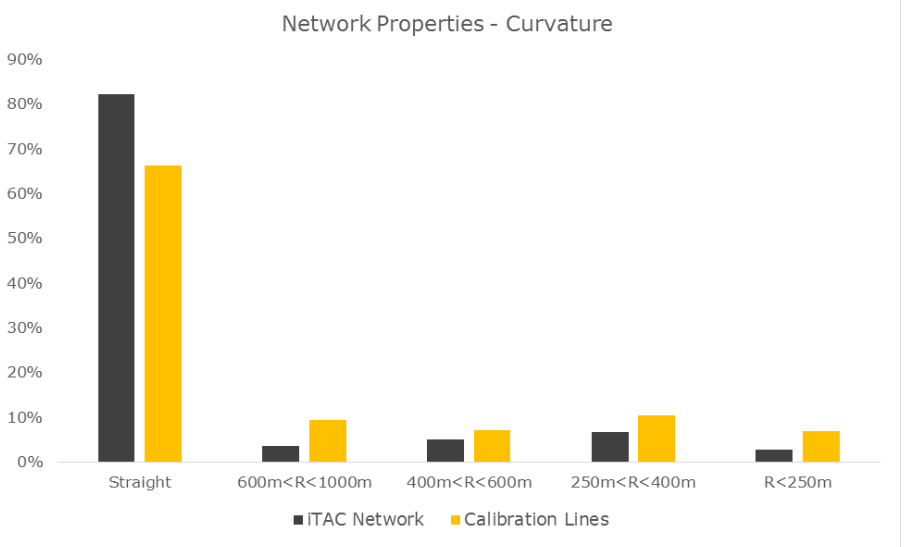

Figure 100 Network Properties - Curvature

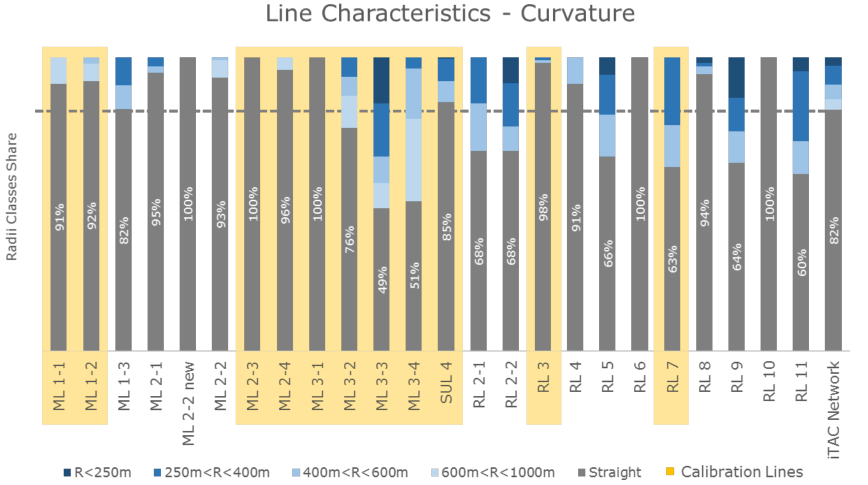

Figure 101 Line Characteristics - Curvature

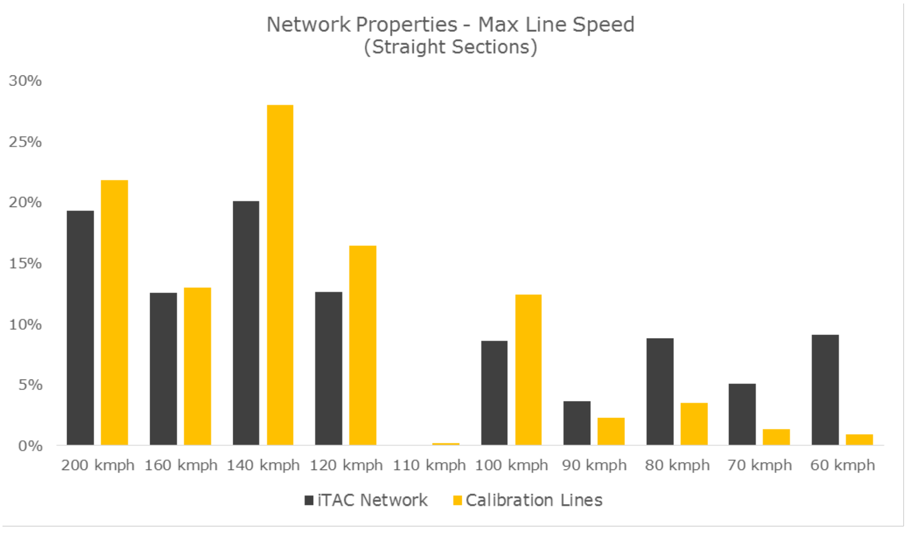

Figure 102 Network Properties - Max Line Speed (Straight Sections)

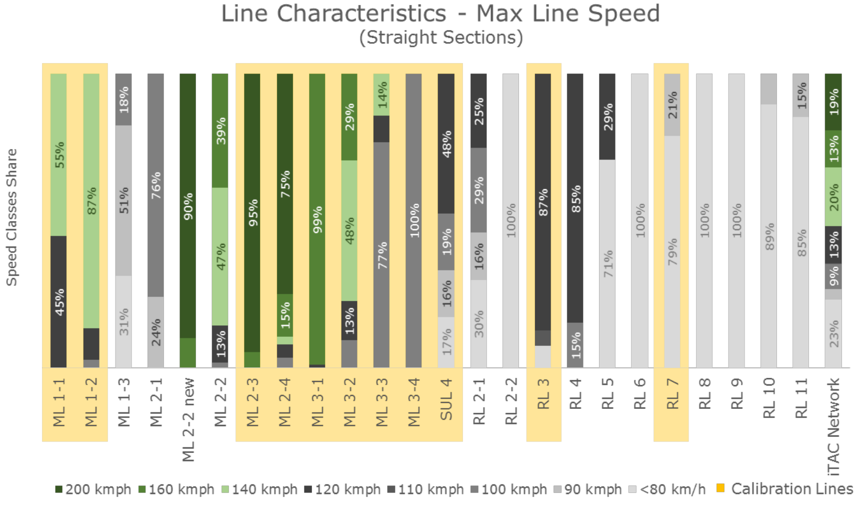

Figure 103 Line Characteristics - Max Line Speed (Straight Sections)

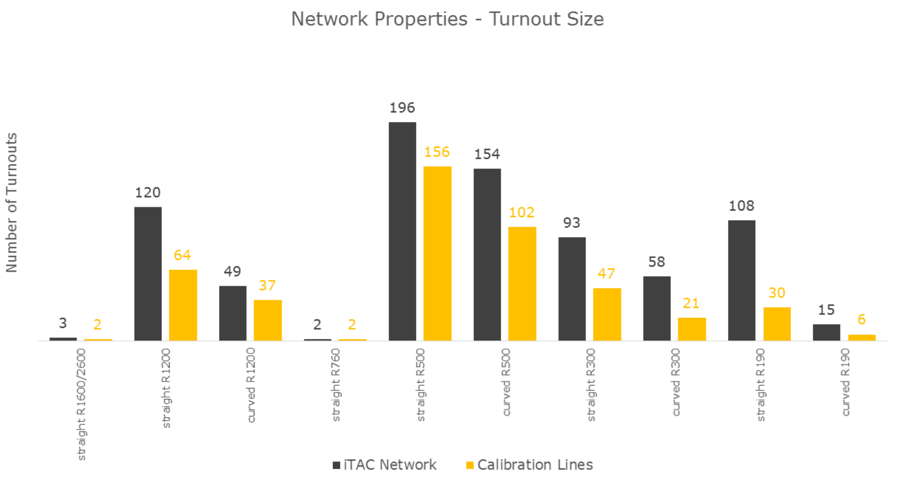

Figure 104 Network Properties - Turnout Size

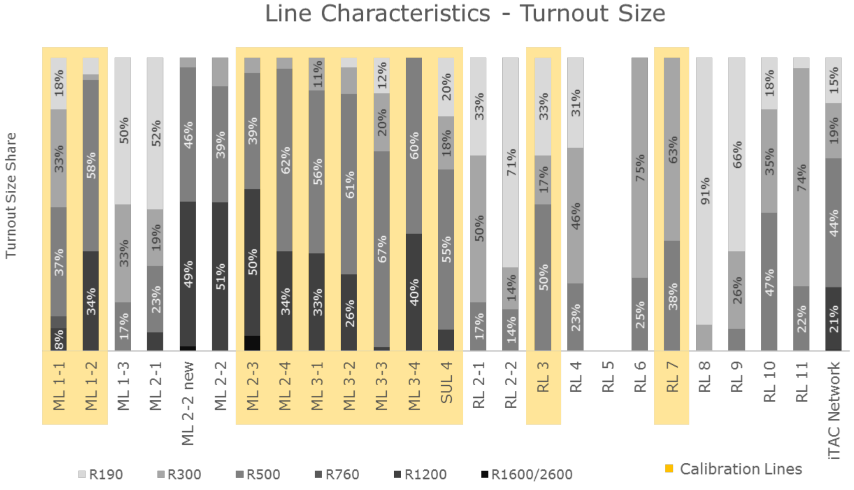

Figure 105 Line Characteristics - Turnout Size

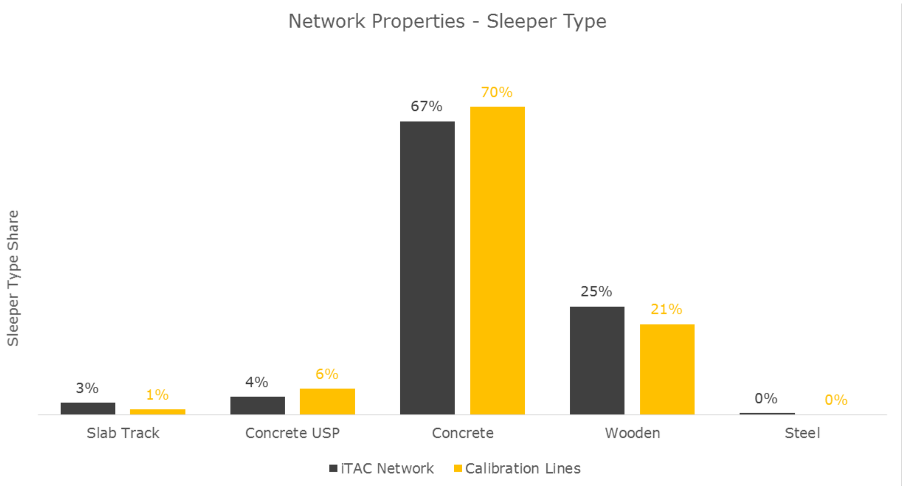

Figure 106 Network Properties - Sleepers Type

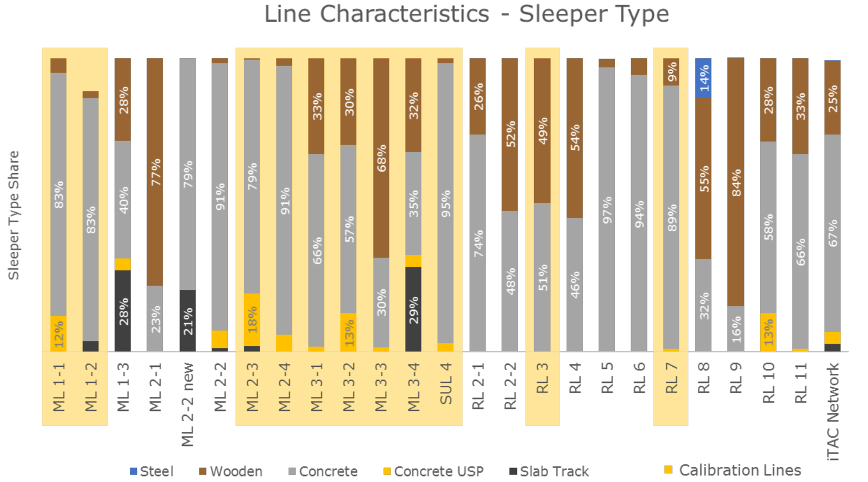

Figure 107 Line Characteristics - Sleepers Type

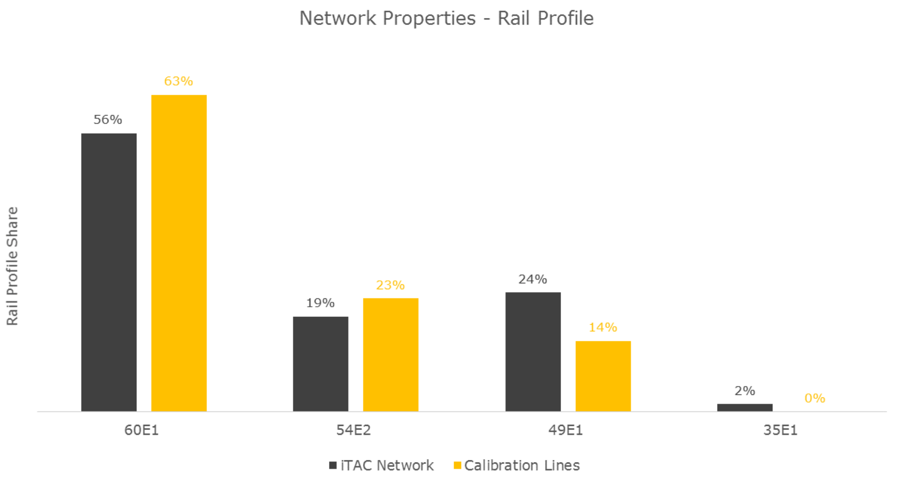

Figure 108 Network Properties - Rail Profile

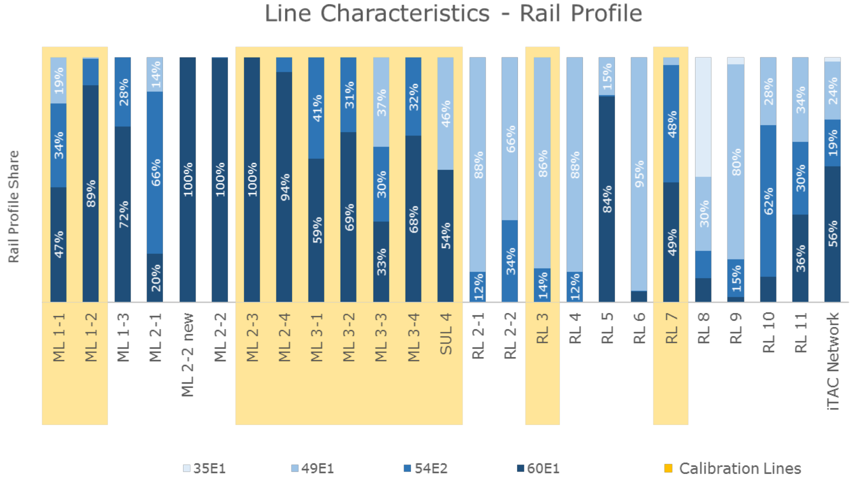

Figure 109 Line Characteristics - Rail Profile