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Holistic embedding of equivalent conicity in wheelset maintenance
Case study of a modern electric multiple unit

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Abstract

With continuing digitization of railways an increasing number of data is recorded but particularly in operation advanced analysis tends to be partially rudimentary. Yet, it is essential to implement sophisticated processing for all records in order to develop more purposeful and predictive vehicle maintenance strategies that adhere to the increasing requirements imposed by the homologation. Typically developing requisites are permissible track forces and lateral accelerations which are directly affected by the vehicle’s condition. The present work addresses this issue by executing a case study focused on a Swiss high-speed electric multiple unit with equivalent conicity being the main parameter of interest. This geometry quantity holds high relevance in determining the running stability of track guided vehicles, respectively in assessment of comfortable and safe operation. Currently, it experiences an increasing significance in the homologation as well. Thus, wheelset maintenance is challenged to elaborately embed equivalent conicity to the other influencing factors in the re-profiling strategy.

A framework is established on how operational data can be analyzed and findings systematically be evaluated. The required records are provided by a Swiss railway operator and majorly processed by visualization as well as statistic tools while considering vehicle design and operational aspects. The subsequent proposition of strategies is accompanied by holistic balancing of vehicle needs, maintenance resources, and vehicle scheduling needs.

As a result, correlations concerning the vehicle’s configuration, design, and operational properties are observed. Incorporating these observations, for example by applying advanced warning limits, enables deduction of more predictive and holistic strategies. The potentially emerging benefits are manifold and range from lower demand on engineering staff, increased mileages, to fewer unplanned servicing tasks and subsequently increased operational stability. Further, the findings emphasize the need for in depth understanding about relevant data to derive more advanced and holistic maintenance strategies.

Keywords
Railway Operation, Equivalent Conicity, Wheelset Maintenance, Smart Maintenance, Data Analysis
Sammanfattning


Avhandlingen föreslår ett tillvägagångssätt för hur data av ekvivalent konicitet och relaterade aspekter kan analyseras och systematiskt implementeras i fordonens reprofileringsstrategi av hjulen. Dokumenten tillhandahålls av en schweizisk operatör och utvärderas huvudsakligen genom visualisering och statistiska verktyg samtidigt som design- och driftsaspekter kontinuerligt prövas. Präsentationen av strategier åtföljs av en helhetlig utvärdering av behov för såväl fordon och underhållsanläggningar som schemaläggningar av driften.

Som ett resultat av detta observeras korrelationer mellan fordonens tekniska egenskaper med design- och driftsegskaper. Genom att inkludera dessa observationer, till exempel genom att tillämpa avancerade varningsgränser, kan mer predikativa och helhetliga strategier föreslås. De potentiella fördelarna är många och kan sträcka sig från lägre behov av ingenjörspersonal, ökad körsträcka, till färre oplanerade serviceuppgifter och leder till ökad driftstabilitet. Vidare betonar resultaten behovet av djupgående förståelse för parametrar för att härleda helhetliga underhållsstrategier.

Nyckelord

Järnvägsdrift, Ekvivalent Konicitet, Hjulset Underhåll, Smart Underhåll, Dataanalys
iv | Sammanfattning
Zusammenfassung


Die Studie erarbeitet einen Ansatz, wie Daten betreffend der äquivalenten Konizität analysiert, und die Erkenntnisse systematisch in die Radsatzinstandhaltung des Fahrzeugs implementiert werden können. Als Datengrundlage dienen die von einem Schweizer Bahnbetreiber zur Verfügung gestellten Datenbanken welche, unter Berücksichtigung von Konstruktions- und Betriebssaspekten, überwiegend durch Visualisierungs- und Statistiktools ausgewertet werden. Um verbesserte, ganzheitlichere Strategien ableiten zu können fließen ergänzende Anforderungen vom Fahrzeug selbst, der Serviceanlage wie auch der Betriebsplanung in die Auswertung ein.

Zustandsindikatoren unerlässlich ist, um ganzheitlichere Instandhaltungsstrategien im Unterhalt etablieren zu können.

**Schlüsselwörter**

Eisenbahnbetrieb, Äquivalente Konizität, Radsatzinstandhaltung, Intelligente Instandhaltsstrategien, Datenanalyse
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Berne, Switzerland, June 2023
Philipp Linzbichler
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<td>( \lambda )</td>
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<tr>
<td>( \Delta )</td>
<td>difference</td>
<td>-</td>
</tr>
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<td>( \Phi )</td>
<td>rotational angel of the wheel</td>
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<td>( CCI )</td>
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<td>( TG )</td>
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<td>( Wz )</td>
<td>Wertungszahl, comfort index</td>
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# Acronyms and Abbreviations

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<td>alternating current</td>
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<td>CHE</td>
<td>Switzerland</td>
</tr>
<tr>
<td>Acronym</td>
<td>Description</td>
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<td>---------</td>
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<td>DB</td>
<td>Deutsche Bahn AG, German Railway</td>
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<tr>
<td>EMU</td>
<td>electric multiple unit</td>
</tr>
<tr>
<td>ERP</td>
<td>enterprise resource planning</td>
</tr>
<tr>
<td>EU</td>
<td>European Union</td>
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<td>EW IV</td>
<td>Einheitswagen IV, single deck passenger coach</td>
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<tr>
<td>FMS</td>
<td>fleet management system</td>
</tr>
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<td>FSD</td>
<td>Frequenz-selektive Daempfung, frequency selective damping</td>
</tr>
<tr>
<td>GPS</td>
<td>global positioning system</td>
</tr>
<tr>
<td>HALL</td>
<td>hydraulisches Achslenkerlager, hydraulic wheelset guidance</td>
</tr>
<tr>
<td>IC 2000</td>
<td>Intercity 2000, double deck passenger coach</td>
</tr>
<tr>
<td>ICE</td>
<td>Intercity-Express</td>
</tr>
<tr>
<td>IoT</td>
<td>internet of things</td>
</tr>
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<td>ITA</td>
<td>Italy</td>
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<td>JPB</td>
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<td>powered bogie, TDG</td>
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<td>RDS</td>
<td>Rail Data Services</td>
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<td>SBB</td>
<td>Schweizerische Bundesbahnen AG, Swiss Federal Railways</td>
</tr>
<tr>
<td>SNCF</td>
<td>Société nationale des chemins de fer français, National society of French railroads</td>
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<td>UB</td>
<td>unpowered bogie, LDG</td>
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<tr>
<td>UFD</td>
<td>Unterflurdrehbank, wheel turning machinery</td>
</tr>
<tr>
<td>UIC</td>
<td>Union internationale des chemins de fer, International Union of Railways</td>
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<td>UMA</td>
<td>Ueberfahrmessanlage, drive-over measurement system</td>
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<td>UWS</td>
<td>unpowered wheelset, LRS</td>
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<td>WTT</td>
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Chapter 1

Introduction

Mega trends like globalization and mobility turnaround reshape societal behavior profoundly. They are driven by environmental factors yielding steady, long lasting change in many aspects of life [1]. Railway industry is particularly affected. The implications can be perceived by looking into passenger volumes and punctuality. In Germany for instance the passenger kilometers per year rose by almost 20% from 2010 to 2019 [2]. Switzerland leads the European comparison in 2019 with 2605 traveled kilometers per inhabitant [3]. The growing demand also implies major challenges for railway operators. In 2019 the long distance services from German railway operator Deutsche Bahn AG, German Railway (DB) managed a punctuality of 75.9% with deteriorating tendency [4]. In contrast, the Swiss railway operator Schweizerische Bundesbahnen AG, Swiss Federal Railways (SBB) achieved in the same year a relatively stable punctuality of 88.0% among their long distance services but knowingly operates close to certain capacity limits [5].

With the advance of mega trends and political initiatives such as "Shift2Rail" from the European Union (EU) it is likely that the importance of railways will continue to grow. As a consequence, stress on all operators increases inexorable. Thus, they are challenged to deal with the growing demand on their services to keep and increase their operational standards. Consequent and innovative development among all units is vital to match this trend and hold up to railways responsibility in promoting modal shift.

1.1 Background

Railway operation builds upon a complex ecosystem consisting of many stakeholders and different, yet mutually depending units. Rail vehicle
maintenance is one integral part of this ecosystem and particularly vital to fundamental operability. It is responsible to provide safe and generally well serviced trains to the operation. Its activities range from short term interventions, over planned revisions to major refurbishments and are typically dealt with in a preventive or corrective manner. The tasks within those activities are wheel re-profiling, component checks, and adjustment works. Further, maintenance is a perfect example of distinct mutual connection between many sub-areas of the railway ecosystem. Particularly important dependencies exist between the maintenance engineering, workshop, and vehicle scheduling. As a result, the deduction of maintenance strategies that add the best value for all parties is a complex task.

1.1.1 Problem

Servicing strategies as of status quo are commonly based on preventive or corrective approaches, governed by empiric considerations such as discrete checking for transgression of condition indicators. These methods are rather robust but lead to tendentially conservative measures. Furthermore, they impede in depth understanding required to implement more predictive and smart maintenance strategies.

The reasons for these conservative standards are manifold but one important aspect is missing understanding for the behavior of certain condition indicators before they actually trigger a warning limit or in fact lead to a damage. As an example, experts from the French railway operator Société nationale des chemins de fer français, National society of French railroads (SNCF) emphasize that establishing more predictive maintenance prerequires roughly 90% monitoring and understanding the data from condition indicators [6]. The consequences emerging from limited comprehension of behavioral aspects can be inefficient suspending of vehicles meaning serious implications for railway operation such as shortened trains and unplanned cancellations. It may also increase the risk of unexpected train failures. Ultimately, passenger satisfaction and cost efficiency decreases.

1.1.2 Scientific issue and Problem statement

As a fundamental part of vehicle servicing the sub-area wheelset maintenance is particularly challenging due to its high relevance in ensuring comfortable and safe running behavior. Further, in depth comprehension of wheel-rail-interaction is still an important matter to fundamental research which under-
lines the difficulty of the task. Many scientific papers have been published describing wear mechanisms and building mathematical correlations between influencing factors. However, the present thesis deals with a thematically related branch. The study generally omits in depth description of wear mechanisms and sets the focus on exploring basic relations between the behavior of equivalent conicity and vehicle design as well as operational aspects. Equivalent conicity as the main parameter of interest is chosen as it experiences an increasing relevance imposed by the homologation. In the process of stability assessment more often fixed operational limits are set for the parameter making its consideration inevitable in maintenance.

Consequently, the thesis addresses the problem of how data concerning equivalent conicity can be purposefully processed and correlations to fundamental design and operational aspects be drawn. It further investigates the embeddability of the findings to holistic wheelset maintenance strategies that account for workshop resources and vehicle scheduling needs.

1.2 Purpose

Literature research as well as internal probing has shown that, as of now, solutions to the elaborated scientific issue are still in their infancy. Furthermore, operators such as SBB currently vastly apply preventive strategies. However, they strive for improving their strategical standards by expanding their understanding for condition indicators such as equivalent conicity and resultingly improve the vehicle’s availability and reduce costs. Thus, the present paper addresses this gap. With the proposed strategies significant improvements for vehicle maintenance can be ascertained. Early experience from SNCF in 2019 has shown that with more predictive maintenance strategies savings in servicing costs of 20% were achievable [6]. Furthermore, the stress on vehicle scheduling can be reduced which leads to increased operability as well as improved disposition of workshop resources due to increased predictability. Summed up, this means improved cost efficiency, rising passenger satisfaction and enables further initiatives to be build upon. In other words, it strengthens railway’s competitiveness and supports modal shift towards sustainable traffic.
1.3 Research methodology

Generally, the study targets three main matters to be researched consisting of "Vehicle needs", "Maintenance resources", and "Vehicle scheduling needs". The work on these pillars is executed as a case study focusing predominantly on one fleet of a Swiss railway operator. This approach is chosen to keep the amount of data manageable. Furthermore, the problem elaborated does not necessarily demand a broader spectrum of research as the study focuses on establishing a general framework that other cases can refer to.

Data analysis is the major research method vastly applied to the records concerning the vehicle, respectively wheel profiles. The data is processed in MATLAB and EXCEL where it is systematically filtered, aggregated, plotted as well as statistically evaluated.

Yet another key method applied to this work are interviews and field research. The former are majorly used to analyze needs on a less technical level from the workshop and vehicle scheduling while the latter is vastly applied to explore processes and practices at the service facility. However, both methods are also essential in establishing the fundamental knowledge that is governing the data analysis.

1.4 Delimitations

The present study is mostly delimited by the nature of a case study. The results drawn do generally not aim for being directly applicable to other cases. Findings concerning equivalent conicity, sub-area needs and boundary conditions are referred to a specific fleet and operator.

It is also important to understand that the data used for this work is mostly rehashed by the provider SBB. Measurements are recorded, checked, and processed by the responsible staff and incorporated to this work without extensive preprocessing. Thus, the measuring principles and related processing is only addressed superficially.

Further, the research does neither explicitly account for monetary evaluation, nor the internal specifics when a new strategy is implemented. Thus, the results must be considered a proposal that requires further assessment by experts from the affected units as well as economic analysis.
1.5 Structure of the thesis

Chapter 2 focuses on fundamentals concerning wheel-rail phenomena as well as maintenance and vehicle scheduling. Each section is contemplated by the literature research. Concluding, the vehicles governing the case study are presented. Chapter 3 dives deeper into the applied methods used to analyze the data. Further, it establishes the general, holistic framework. In Chapter 4 the findings from the data analysis are presented individually and in a holistic context, concluded with the proposition and discussion of potential wheel re-profiling strategies. Chapter 5 concludes the present thesis by pointing out limitations and opportunities for future research.
6 | Introduction
Chapter 2

Background

In the following, the backgrounds and current scientific research relevant to this study are presented. Fundamentals concerning wheel-rail-interaction are elaborated in Section 2.1, rail vehicle maintenance in Section 2.2, and vehicle scheduling in Section 2.3. Concluding, Section 2.4 motivates the case.

2.1 Wheel-rail interaction

Wheel-rail interaction concerns a broad field of topics ranging from running behavior, creepages, and wheel and rail wear mechanisms. Running behavior sets the particular field of interest for this work focusing on the theoretical aspects governing equivalent conicity and running stability of rail vehicles.

2.1.1 Equivalent conicity

Figure 2.1b plots the geometrical features of contact point pairings between wheel and rail showing that they are far from constituting a perfect conical pairing geometry. Thus, the so called equivalent conicity is introduced which quantifies the wheel-rail contact geometry and significantly concerns assessment of a vehicle’s running stability. This parameter can be computed either referring to [7]

$$\lambda_{eq} = \frac{r_r - r_l}{2\Delta y}$$

(2.1)

or [8]

$$\tan \gamma_{eq}(y) = \frac{1}{\pi y} \int_{0}^{2\pi} \frac{1}{2} \Delta r (y \sin \Phi) \sin \Phi d\Phi,$$

(2.2)
whereof $\lambda_{eq}$, respectively $\tan \gamma_{eq}$ are the dimensionless equivalent conicity with respect to a lateral wheelset displacement along the $y$-coordinate, $r$ describes the rolling radius of the wheel, $\Phi$ the wheels rotational angle, and $\Delta$ the difference of the subsequent factor. $\gamma_{eq}$ defines the equivalent conical angle in the contact point of wheel and rail. Figure 2.1a pictures these parameters.

Figure 2.1: Contact point properties

Due to the geometrical nonlinearities, which are further exemplified by Figure 2.2a plotting the difference of rolling radius over lateral wheelset displacement, evaluation of the Equations (2.1) and (2.2) yields the general nonlinear function of equivalent conicity plotted in Figure 2.2b. However, usually the relevant concentration of amplitudes of the wheelset’s hunting motion is within the range of $\pm 3$ mm to $\pm 4$ mm [7]. Thus, many applications refer to the standard Union internationale des chemins de fer, International Union of Railways (UIC) 518 and 519 by specifically assessing equivalent conicity at $\pm 3$ mm lateral wheelset displacement [9, 10]. Another method is to compute the averages of conicities for a defined range of amplitudes [7]. A fourth approach called ”DB-Method” assumes sinusoidal movement and superimposes it with the nonlinear $\Delta r$-function [8].

Figure 2.2: Nonlinear contact point behavior
Influencing factors
The magnitude of equivalent conicity is generally governed by the rail profile, gauge, inclination, irregularities such as small gauge deviations, height offsets etc. as well as the wheel profile, gauge, and irregularities such as tread defects, wheel out of roundness etc.

Considering the infrastructure, track gauge, rail inclination and rail profile constitute the major influence in the computation. Generally, equivalent conicity increases with track gauge below nominal as well as decreasing rail inclination. Additionally, irregularities such as track gauge deviations impact the computation with every increment of track [7, 8].

From the vehicle’s point of view the wheel profile and gauge predominantly define the magnitude of equivalent conicity. Different wheel profiles exist but among the most common ones are the UIC S1002 and the "worn-profile" EPS which are discussed in more detail in Section 2.1.3. Generally, their geometries change with mileage leading in some kind of tread and flange wear. The exact wear schemes depend on the technical configuration such as the wheelset being powered as well as track features and operational aspects. Two wheel profiles exemplifying this are plotted in Figure 2.3. Thick flanges and hollow worn wheel profiles are wear schemes that increase equivalent conicity, while thin flanges affect vice versa [7].

![Figure 2.3: Wheel wear of a Swedish commuter train plotted in mm [11]](image)

2.1.2 Stability
The running behavior of a train is generally considered stable when pronounced hunting motion from an initial deflection damps out and does not sustain or even increase. The limiting factor deduced is the vehicle’s critical, respectively maximum speed. Figure 2.4 exemplifies this behavior of hunting motion for a simple wheelset acting completely linear. It pictures the behavior below and above the critical linear speed. However, due to nonlinearities within the system the actual wheelset’s lateral amplitude does not increase
infinitely when running at or above critical velocities. The magnitude is
governed by a limit cycle that depends on the initial lateral deflection and the
system’s speed with respect to the linear critical and nonlinear critical speed.
However, for this work it is sufficient to understand that the nonlinear critical
speed is generally below the linear critical one, making it particularly relevant
in determining a vehicle’s design speed [7].

![Figure 2.4: Wheelset oscillation with respect to velocity adapted from [7]](image)

Assessing stable running is also a highly important aspect in homologation
of rail vehicles. The exact process is given by EN 14363 but generally it must
be demonstrated that a train can safely approach its design speed under certain
boundary conditions. Commonly, the bar is set even lower by demanding
a comfortable state which is verified by evaluating the accelerations within
the carbody and assess them with the Wertungszahl, comfort index \((Wz)\). The calculation procedure is shown in [7] where it is also discussed that the
acceptable magnitude depends on the train’s expected application.

**Influencing factors**
Equivalent conicity significantly influences stability. Figure 2.5 pictures a
simple case, comparing a free wheelset with a stiffly suspended one. It shows
that increasing speed and higher magnitudes of equivalent conicity lead to a
notable increase of hunting frequency. Furthermore, the unstable condition
is shifted to lower speeds. Thus, higher velocities generally demand low
equivalent conicities achieved by limiting the differences in rolling radius.
This reduces the circumferential speed divergences between left and right
wheel and resutlingly enhances straight drive. As a rule of thumb, speeds
up to 250 km/h demand a value below 0.3 [7]. Figure 2.5 also shows that the
actual speed limit depends on even more factors like the vehicle’s configuration
such as wheelset suspension and guidance. Further influencing factors are the
vehicle’s mass as well as operational and network specifics.
2.1.3 Literature research

The study’s literature research on wheel-rail interaction focuses on advanced approaches to process records of equivalent conicity and fundamental backgrounds that are relevant to this study.

Introductory to this section, the calculation methods are elaborated whereof the basic approach computing discrete values for equivalent conicity at specific lateral wheelset displacements still enjoys great popularity. However, it is continually questioned in terms or relevance. Thus, research such as [12, 13] deals with the recently proposed nonlinearity parameter ($NP$) which extends the possibilities in wheel-rail contact geometry assessment. It describes the gradient between two discrete equivalent conicity values $\lambda_2$ and $\lambda_4$ at 2 mm, respectively 4 mm lateral wheelset displacement as

$$NP = \frac{\lambda_4 - \lambda_2}{2}. \quad (2.3)$$

While equivalent conicity usually increases with mileage, $NP$ tends to decrease while having negative values [13]. [12] motivates this with the increasing contact conformity between wheel and rail caused by wear. Consequently, the very same paper proposes the contact concentration index ($CCI$) to further evaluate the contact conformity (see also Figure 2.1). The $CCI$ quantifies the concentration of contact points within a certain bandwidth on the wheel profile. Generally, the larger the bandwidth for the same quantity of contact points, the closer $CCI$ is to 0 and the more likely the tread can achieve a dimensionally stable geometry [14]. Figure 2.6 plots the $CCI$ for different wheel-rail pairings and rail inclinations (Schienenneigung). Particular focus shall be put on the 1:40 rail inclination plot’s S1002 60E1 bar.
and the 1:20 rail inclination plot’s EPS 60E1 bar. They show, that the S1002 profile performs best on 1:40 inclined rails while the EPS is superior on 1:20 inclined rails. This can be motivated by the fact that the S1002 profile was developed for 1:40 rail inclination while the “worn” EPS profile was developed in the United Kingdom, where the network applies 1:20 rail inclination [15]. Relevant literature is referred to for details on the profile geometries.

![Figure 2.6: The CCI for different wheel-rail pairings [14]](image)

*NP* and *CCI* expand the opportunities in assessing the geometrical contact properties of wheel and rail. However, they are yet to be widely established in operational practice.

Due to its curvy layout, the Swiss railway network generally uses high equivalent conicities emerging from the low rail inclination of 1:40. Table 2.1 underlines this by comparing the 50th, 95th, and 99th percentile of the track conicities as a function of speed for Switzerland and Italy. The latter uses higher inclinations of 1:20 reducing equivalent conicity significantly [16]. This comparison is particularly relevant, as the train being introduced in Section 2.4 predominantly operates in these two countries.

Table 2.1: Network equivalent conicities computed with a normative S1002 wheel profile at *y*=3 mm in Switzerland (CHE) and Italy (ITA), based on [16]

<table>
<thead>
<tr>
<th>Speed [km/h]</th>
<th>CHE 50%</th>
<th>ITA 50%</th>
<th>CHE 95%</th>
<th>ITA 95%</th>
<th>CHE 99%</th>
<th>ITA 99%</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-120</td>
<td>0.20</td>
<td>&lt;0.05</td>
<td>0.45</td>
<td>0.15</td>
<td>0.65</td>
<td>0.20</td>
</tr>
<tr>
<td>120-160</td>
<td>0.20</td>
<td>&lt;0.05</td>
<td>0.30</td>
<td>0.15</td>
<td>0.50</td>
<td>0.20</td>
</tr>
<tr>
<td>160-230</td>
<td>-</td>
<td>&lt;0.05</td>
<td>-</td>
<td>0.10</td>
<td>-</td>
<td>0.15</td>
</tr>
</tbody>
</table>
2.2 Rail vehicle maintenance

Maintenance of a rail vehicle is an integral part to the railway ecosystem. Its responsibility is to ensure a vehicle’s safe and generally satisfying condition. Many operators maintain their rolling stock at the overall system level leading to suspending of vehicles for a couple of days. SBB in turn services predominantly on component level focusing on maintaining them at the very best time rather than strictly exploiting task synergies within overall systems such as the bogie. The maintenance division focuses on applying lean management principles by relying on just-in-time deliveries of spare parts and keeping many aspects of service in-house. Thus, individual lead times at SBB are short but vehicles may be suspended more frequently.

2.2.1 Wheelset maintenance

Wheelset maintenance is particularly important in ensuring a safe vehicle. Hitherto, wheel re-profiling and wheelset change strategies are mainly driven by periodically conducted measurements where transgression of certain warning limits indicates the need for action. Typical indicators are wheel gauge, flange thickness and flange height as they might interfere with infrastructure and subsequently lead in damages or derailment. Further, wheel gauge is often considered as a quasi-stability indicator as it describes for each wheelset the distance between the wheel’s flange transitions. Thus, it implicitly indicates how soon and rapidly the difference in rolling radius, respectively equivalent conicity increases with lateral wheelset displacement. SBB trains traditionally use rather soft wheelset guidances to cope with the curvy network. Contrary to the experience at many other operators this leads to increasing flange thicknesses. Further, a trend towards more parameters in the list of relevant indicators can be perceived. Examples are hollow wheel tread and equivalent conicity [17]. The former can cause "flange to false flange" vibration triggered by an almost immediate change of the wheel-rail contact point between two equilibrium positions. As a consequence, the vehicle dynamics, particularly at higher speeds, are worsened. Interestingly, hollow worn wheels can also improve curving due to increased diameter differences, thus impact equivalent conicity as well [18]. SBB implemented equivalent conicity as a stability indicator in 2016 due to abnormalities in hunting motion of some passenger coaches, which will be addressed in more detail in Section 2.4. Since equivalent conicity can not directly be measured the calculation procedure based on Equations (2.1) and (2.2) considers the real
profile shape of the wheel and evaluates it referring to a normative track profile. Details are provided in Section 3.1.2. It is worth mentioning that equivalent conicity is currently checked manually on a case by case principle. Another indirect type of indicator for abnormalities are physical perceptions from staff and warnings from the condition monitoring which can lead to fault reports.

Depending on the severity of transgression or damage the remaining kilometers before wheel re-profiling or wheelset change must be conducted are usually limited to 20,000 km. Once in the workshop, the machining strategies vary depending on the position and severity of defects as well as tolerable wheel diameter differences and limits, the vehicle’s general design etc.

To match with servicing strategies aiming for shortened lead times and reduced frequency of vehicle suspending wheelset maintenance is challenged to continuously improve and implement more holistic strategies. SBB for example initialized the MATCH strategy establishing a holistic approach that accounts for improved understanding of available data and needs beyond the wheelset itself such as workshop resources and vehicle scheduling. Such initiatives are supposed to path the way for more predictive strategies, thus increase reliability and availability while reducing costs.

2.2.2 Literature research

The literature research addresses enhancements to wheelset maintenance as well as servicing as a whole. It shows that numerous papers exist but the gap addressed by this study is yet to be filled.

Papers such as [19, 20] deal with risk-based tools to improve preventive maintenance. This is highly relevant as rail vehicle maintenance still relies heavily on preventive strategies. The general aim is to systematically incorporate risk measures to the planning of interventions to improve the scheduling and prolong intervals.

Moving one step further, [21] deals with predictive maintenance stating that most generalized it can be formulated as in depth understanding of equipment behavior and deducing initiatives based on indicators. As a result, it allows for maintenance activities being scheduled well in advance, thus maximizing the usage interval of equipment and minimizing costs. The very same paper further underlines the prerequisites required to implement predictive maintenance successfully such as efficient data collection and profound understanding of the data. The railway related case study from
[22] addresses this issue as well by building a data-driven model that relates the wheel diameter, flange thickness, wear rates, and the re-profiling gain. From this in depth understanding for certain parameters the paper deduces optimized indicator thresholds. Applied to a metro in Guangzhou, the study proves benefits such as prolongation of intervals between wheel re-profiling. A similar study from [23] focusing on historical wear data validates the relevance of such approaches as well.

[24] elaborates that the internet of things (IoT) even enables real-time supervision of data generated by operating equipment. This data can then be processed by model software and a prognosis on the remaining useful life be deduced. That way the step from predictive towards smart maintenance is taken which builds upon four pillars namely data-driven decision-making, human capital resource, internal integration, and external integration [25]. Research from [26] evaluates the benefits emerging from smart maintenance applied to railway industry predicting potential cost reductions which are validated by studies concerning different applications as in [27].

### 2.3 Vehicle scheduling

The general palatability of the railway system’s offerings is highly dependent on the timetable. However, its robustness strongly relies on the vehicle scheduling which ensures that the correct train is available at the right time and place. For this purpose, a working timetable (WTT) is set up that specifies a units successive services over a certain time span. In heterogeneous main line applications rather long time spans are used [28]. Further, the WTT incorporates suspending days for planned maintenance.

However, one of the major challenges in establishing as well as executing a WTT with relation to this study are disruptions from short notice maintenance tasks, limitations on the vehicle or even breakdowns. First, the immediately planned services must be delayed or canceled meaning further implications on connecting trains. Second, sequential services must be covered by backup trains at the desired starting location with similar properties to the intended unit. Third, the broken train must be replaced for the remaining WTT services. Summed up, major challenges arise for operation as many resources are occupied to solve the problem while customer satisfaction decreases.
2.3.1 Literature research

The requirements on vehicle scheduling, respectively the WTT, overlap with aspects from general fleet management system (FMS) which is used in many other applications. Thus, the literature research expands to this area.

Research of [29] states that fleet-route planning, as an integral part of FMS and a more general pendant to the WTT, must deal with many influencing factors. The paper elaborates difficulties on tactical level where events such as seasonality and trends impact the demand on the offerings. [30] addresses this issue by proposing a model that schedules maintenance tasks within a given period and vehicle demand from the timetable. On an exemplary case, the model proves its ability in establishing an optimized WTT. Furthermore, [29] discusses real-time events where adoptions to daily dynamics such as weather and breakdown of equipment are required. It validates that these unexpected events constitute a major challenge and must be handled by a real-time dynamic FMS. Also, it puts forward that smart cyber-physical systems will support the reduction of decision time when experiencing real-time events.

2.4 Case study

The case study is motivated by elaborating backgrounds and technical features of the vehicles studied. All are operated by SBB on 1435 mm track gauge in predominantly medium and long distance services. Figure 2.7 shows the three vehicles of interest: The electric multiple unit (EMU) series RABe 501, and the passenger coaches Einheitswagen IV, single deck passenger coach (EW IV) and Intercity 2000, double deck passenger coach (IC 2000).

![RABe 501](image1)

(a) RABe 501

(b) EW IV [31]

(c) IC 2000 [32]

Figure 2.7: The three SBB vehicles investigated in this case study
2.4.1 Electric multiple unit - RABe 501

The RABe 501 is a single-deck EMU with distributed traction. With date of this thesis 29 trains are operated by SBB, each offering 405 seats and certified to operate in Switzerland, Italy, Austria, and Germany. The layout of the 11 cars unit is shown in Figure 2.8 where it can be seen that one unit features 12 two-axled bogies of three different types: leading unpowered bogie, ELDG (LUB), jacobs unpowered bogie, JLDG (JUB), and jacobs powered bogie, JMDG (JPB). In total, this makes 24 wheelsets of which eight are powered (black circles). All wheels have an EPS profile. The EMU’s design speed is 250 km/h but limited to 230 km/h on the Swiss network. It is equipped with stability supervision that continuously monitors lateral accelerations on the bogie frames. Depending on the severity a notification is shared to the on-board staff as well as the central service desk which can trigger a fault report. If transgressed significantly the train can limit its speed automatically.

![Figure 2.8: Layout of the RABe 501 (Figure provided by SBB)](image)

The LUB is presented in Figure 2.9. It is connected to the carbody by means of a bolster which constitutes the interface to the secondary air suspension, anti-roll bar and a king pin. The king pin in turn is connected to a lemniscate traction link, lateral dampers as well as bump stops. On primary level coil springs are used. The wheelset guidance is of type hydraulisches Achsenlenkerlager, hydraulic wheelset guidance (HALL) which benefits radial steering at lower and stability at higher velocities. As a result, noise and wear are reduced as well. Disc brakes are mounted to the wheels. The wheelbase is 2700 mm. To further suppress hunting motion at higher speeds while limiting deterioration of the curving and switch-running capabilities the LUB features four Frequenz-selektive Daempfung, frequency selective damping (FSD) yaw dampers connecting bogie frame and carbody.
The JUB and JPB are shown in Figure 2.10. Their general layouts are similar consisting of a swivel joint interconnecting the two carbodies to the bogie. The joint in turn is connected to a lemniscate traction link, lateral dampers as well as bump stops. Further, the four secondary air suspensions are each two directly connected to the carbody and feature the interfaces for the anti-roll bars. On primary level coil springs are used. Disc brakes are mounted to the wheels. The wheelset guidance is of type HALL and the wheelbase is 2750 mm. Two FSD yaw dampers per carbody are connected to the bogie frame. Additionally, the carbodies are interconnected with longitudinal dampers. The traction motor of the JPB is directly connected to the wheelset axle by means of a gear coupling. With alternating current (AC) the EMU continuously provides 4720 kW.

Inducement

Within the homologation process for the Swiss network based on EN 14363 the certifying body SBB Netzzugang capped the maximum speed of the EMU at 230 km/h with a maximal permissible equivalent conicity of 0.41. It was found that particularly the LUB is prone to reaching stability limit cycles and exceeding track forces. However, also the JUB and JPB reached certain limits. As a consequence, the warning limit for equivalent conicity in normal operation was set at 0.35 and 0.4 as the alarm limit. Generally, the lower the maximum permitted equivalent conicity the more often wheels must be re-
profiled since worn wheels tend to have higher equivalent conicities. As a rule of thumb, permitted equivalent conicities of 0.4 should allow for a wheel re-profiling interval duration of approximately 300,000 km [7]. However, early experience shows that the EMU tends to become unstable at higher speeds when exceeding 250,000 km.

Particularly in the introduction phase of the RABe 501, wheel damages occurred that led to very short revision intervals. However, even current re-profiling intervals show rather short distances in the order of 200,000 km.

Further, a sophisticated machining strategy referring to advanced understanding of wear indicators is yet to be applied. It must be settled at what prevailing conditions which wheels are turned. As of now, most commonly all wheels are re-profiled if a distance >250,000 km is reached, otherwise a case by case principle is applied.

### 2.4.2 Passenger coaches

Supplementary, two types of passenger coaches with equivalent conicity supervision as well are included. Figure 2.11 shows their layout.

![Figure 2.11: Layout of the passenger coaches (Figure provided by SBB)](image)

With date of this thesis more than 500 single deck EW IV passenger coaches with up to 80 seats each are operated by SBB. Different types such as driving trailers and conventional passenger coaches exist. Their maximum speed ranges from 160 km/h to 200 km/h. The bogie design slightly varies with the type of car but the most common one is the conventional, two-axled unpowered bogie, LDG (UB) with S1002 wheel profiles as shown in Figure 2.12. On primary as well as secondary suspension level coil springs are used. The interface to the carbody is a bolster with king pin that connects to a lemniscate traction link as well as lateral dampers and bump stops. Two conventional yaw dampers interconnect bogie frame and carbody. The wheelset guidance varies and is either conventional or of type HALL. Disc brakes are mounted to the axle. The wheelbase is 2500 mm.
2.4.2.2 Double deck passenger coach

With date of this thesis more than 300 double deck IC 2000 passenger coaches featuring up to 120 seats each are operated by SBB. Several car types exist like conventional cars and driving trailers. The bogies allow for a maximum velocity of 200 km/h and slightly vary depending on the connected carbody. However, the most general version is shown in Figure 2.13. It is a conventional two-axled UB with S1002 wheel profiles. Coil springs are used on primary and air springs on secondary suspension level. The current bogies are equipped with two electrically activated yaw dampers but are upgraded to FSD yaw dampers as part of a major refurbishment. The interface to the carbody is a bolster connected to a king pin, lemniscate traction link, lateral dampers and bump stops. The wheelset guidance is of type HALL. Disc brakes are mounted to the axle. The wheelbase is 2500 mm.

Inducement

The passenger coaches were put into service well before equivalent conicity monitoring was established at SBB. However, abnormalities in hunting motion of the EW IV and IC 2000 coaches in 2016 led in supervision of equivalent conicity and introduction of the warning limit 0.35 and the alarm limit 0.4 for both passenger coach types. Thus, they have a good data basis and are a valuable supplement to this study majorly used as a reference and comparison. Usually, all eight wheels are machined when a car is suspended for re-profiling.
Chapter 3

Methods

This chapter deals with the research methods relevant to process the prevailing data and information. Section 3.1 elaborates the vehicle’s data origin, the databases with respect to the quality of the records as well as the applied analysis methods. Further, the assessment of the maintenance and vehicle scheduling needs is discussed in Section 3.2. The chapter is concluded with Section 3.3 elaborating how the three main pillars are processed in order to deduce holistic strategies.

3.1 Vehicle data

SBB extensively collects data of its vehicles ranging from measurements of dynamic loads over wheel profile measurements to manually written reports. The required equipment is either installed permanently to tracks, vehicles, and facilities or applied manually. With data from complete wheel profile measurements, equivalent conicity can be computed. Further, fault reports and on-board condition monitoring may indicate correlations to equivalent conicity as well. Thus, the subsequent sections elaborate the relevant devices for complete wheel profile measuring, the principles of fault reports and on-board condition monitoring as well as the related databases storing the records.

3.1.1 Measurement devices

Generally, SBB applies a great variety of measurement equipment but for geometric quantities of wheel profiles four types of instruments are used. Three of them are capable of recording the complete tread and flange profile.
Wheel turning machinery
The Unterflurdrehbank, wheel turning machinery (UFD) is the wheel re-profiling machinery used at the workshops in Zurich, Basel (see Figure 3.1b) and Geneva. It is the main tool used for wheel profile machining but also holds high relevance as a measurement device. A mechanical system palpates the flange and tread before and after the machining and records the contour. The principle is shown in Figure 3.1a. The systems used by SBB achieve accuracies of $\pm 0.5$ mm whereof the contour measurement is tendentially more accurate.

Drive-over measurement system
In contrast to the UFD the Ueberfahrmessanlage, drive-over measurement system (UMA) measures wheel profiles from moving train sets. SBB has three drive-over measurement systems from DMA Italy which are installed to car washes in Zurich, Basel (see Figure 3.2), and Oberwinterthur. These specific locations were chosen due to relatively high variation and frequent use of trains running at slow speeds. The permitted velocity for recording is 1 km/h. The measuring principle is optical with accuracies of $\pm 1$ mm whereof the contour measurement is significantly more accurate.
Hand held measurement system
Calipri is a widely used hand held wheel profile measurement device which is shown in Figure 3.3. It requires a train at stand still and recording must be conducted fully manual on a wheel by wheel principle [35]. The system is laser based and achieves accuracies of $\pm 0.5\,\text{mm}$ whereof the contour measurement is tendentially more accurate.

![Calipri handheld measurement device](image)

Figure 3.3: Calipri handheld measurement device [36]

3.1.2 Wheel profile measurements
The wheel profile records such as flange thickness, flange height, hollow wheel wear, wheel gauge, contour etc. are processed into a database called C2M. Further, meta data such as wheelset and bogie type, service facility, and date are stored. Since equivalent conicity cannot directly be measured an external tool computes it by means of Equation (2.2). There, the real wheel profile contour data is paired with a normative track profile EN13674 60E1, 1435 mm track gauge, and a rail inclination of 1:40 as commonly applied in Switzerland. The tool computes equivalent conicity for lateral displacements of the wheelset for every quarter of a millimeter but specifically prints it at 1 mm, 2 mm, 3 mm, and 4 mm. The results are returned to the C2M database. The resulting database is rather large and heterogeneous. Filtered for the relevant vehicles until November 2022, it features 393608x81 cells.

Data quality
Depending on the principle, SBB regards most wheel profile measurements concerning equivalent conicity as exact enough starting with approximately 2021. Older data should solely be used with caution.

In case of minor defects on the wheel profile the UMA is able to minimize
the error by averaging multiple measurements. For Calipri in turn the user is responsible to choose an appropriate measuring position on the wheel tread. General exceptions in recording are made when new wheels are fitted to the axle. Usually, these are delivered pre-measured with a measurement protocol which is directly uploaded to the database. Further, wheelset changes are detected by wheel diameter jumps >15 mm. This heuristic is relatively stable but particularly the EW IV coaches have some faulty intervals recorded due to uncommon wheelset changes. These led into some wrongly connected equivalent conicities and kilometers since last wheelset revision. However, for the majority of data sufficient quality is ensured by SBB’s responsible staff.

Another relevant aspect concerning the prevailing data is the varying frequency of recording. Maximal intervals for measuring a vehicle are commonly set in the order of 90 days or 45,000 km. They are not strictly adhered to but certainly not exceeded. Additionally, measurements may be triggered erratically by inspections and fault reports. Censorship impacts the data as well. It describes the reset of records for one cycle of wheel profile wear caused by (early) re-profiling.

3.1.3 Fault reports
Fault reports are handled manually by staff. Whenever relevant anomalies are detected or vehicles are registered for re-profiling a form is filled. It contains metadata, a case description and the required actions. These reports are often logically connected to the C2M database but as of now saved separately and unlinked to an enterprise resource planning (ERP) database. Until the end of 2022, 3593 reports deal with the vehicles of interest.

Data quality
The fault reports must be assessed carefully. They are filled fully manual occasionally leading to incomplete, inconsistent or meaningless records. Often, copy-paste texts are used to describe similar, yet not identical issues. Thus, the relevance must be checked on a case by case principle and in accordance with the other databases.

3.1.4 Condition monitoring
The manufacturer of the RABe 501 provides operators with a database called Rail Data Services (RDS) that stores all notifications generated by the on-
board condition monitoring as well as meta data like location from the global positioning system (GPS).

Particularly interesting are records from the stability supervision of the RABe 501 which rely on accelerometers attached to the bogie frame close to the wheelset. Ten or more consecutive oscillations of excessive lateral accelerations within frequencies of 3 Hz to 9 Hz trigger a warning. Multiple concurrent stability issues on different bogies may also result in sum warnings. The severity depends on the magnitude of accelerations, duration, and sum of signals and is ranked with priority A to D. A denotes the most severe issues that lead to an immediately forced speed reduction. Usually, they emerge from B warnings due to insufficient driver action. A and B notifications are supervised over the whole speed range while C warnings are exclusively monitored at velocities above 200 km/h. The generated notifications hold information on severity of the issue, prevailing speed, implications, position, time, duration etc. Supplementary, valuable insights are also derivable from meta data about the unit’s position or other notifications. Considering all warnings for the RABe 501 that deal with relevant stability issues until the end of February 2023 a total of 932 notifications are obtained.

Data quality
The general quality of the RDS database cannot be examined independently as it is within the manufacturers responsibility. However, the data used for this work does not indicate any doubt on plausibility but shows some weak spots such as missing information on certain warning codes and older notifications. An example is velocity in tunnels which is often missing or must be extracted from other notifications.

3.1.5 Data analysis
Considering the case relevant vehicles and prevailing data more than 10,000 potentially sensible data groupings exist. To process them a tree-like structure is chosen. Figure 3.4 pictures the approach for the RABe 501 showing two exemplary columns for equivalent conicity at 1 mm and 2 mm lateral wheelset displacement. The actual tree further expands horizontally to equivalent conicity at 3 mm and 4 mm lateral wheelset displacement. The analysis starts with the first row which is the coarsest level where all data is merged. With every row the grouping possibilities are refined and expanded. Resulting plots, meta data etc. are stored to a log for further assessment. All entries are codified to ease classification when being processed. Analyzed groups as well
as abnormalities are marked in a log-matrix. Generally, the aim is not to assess all combinations but follow the branches that appear most relevant.

![Tree-like data analysis structure for the RABe 501](image)

**Figure 3.4: Tree-like data analysis structure for the RABe 501**

### 3.1.5.1 Software

The coexistent databases C2M, **ERP** and **RDS** do not feature the required analysis tools and obstruct concatenation of the databases. Thus, additional software must be applied.

**MATLAB** is chosen to majorly process the database C2M. On the one hand, the sheer amount of data demanded a programming based approach. Aggregating this much data, calculating supplementary variables such as the \( NP \) and storing the results is computationally expensive. On the other hand, this software is widely used in scientific research and engineering. It offers a programming language embedded to a desktop environment featuring pre-implemented functions to analyze and visualize data. Further, functions
specifically adapted to the own needs can be implemented [37]. The software is particularly powerful when homogeneous, numerical data is processed. For the present work it is predominantly used to import the records, condition, aggregate, filter, and group them. An important conditioning aspect for example emerges from missing records. Particularly the very first lifecycle and interval do not hold data on the kilometers since last re-profiling. This is due to the wheelset and unit being totally new, neither requiring a preceding re-profiling activity, nor having records on the kilometers since last wheelset change. Yet, this data must be considered relevant. Thus, the total mileages are linked as a substitute parameter. The most important applied filters concern fleet, lifecycle and interval specific arguments. Further, variables like the $NP$ and nonlinearity parameter 2 ($NP^2$), which will be introduced in Chapter 4, are computed and added to the database. The resulting data is processed by plot and statistic functions facilitating various evaluation procedures.

Microsoft EXCEL is used to deal with the smaller, highly heterogeneous databases from ERP and RDS. The well-known spreadsheet calculation software is also very powerful in terms of data processing and advantageous for evaluation without a specific routine. Instead, the ability to manually interact with the data and easily apply certain filters as well as plot tools is highly valuable.

3.1.5.2 Evaluation

The fault reports and condition monitoring records are concatenated to the C2M database by using timestamps and the UIC based train numbers. The evaluation of this data is conducted according to the analysis tree building upon three main methods.

Scatter plots & Histograms

Scatter plots visualize discrete data points over parameters of interest. Consequently, trends, scattering, transgression of warning limits, differences within groups etc. can be assessed. Further, histograms visualizing data density support the evaluation procedure as many data points overlap, thus impede visual assessment. These methods are predominantly applied to records from equivalent conicity at differing lateral wheelset displacements plotted over kilometers since last re-profiling. Furthermore, evaluation of $NP$ and $NP^2$ builds upon the same methods.
**Line plots**
In contrast, line plots connect discrete data points with straight lines, thus facilitate improved visualization of data behavior. Its sensibility is limited to smaller, individual data groups making it powerful in evaluating specific cases. As a result, this method holds high relevance in assessing equivalent conicity, $NP$, and $NP^2$ plotted over kilometers since last re-profiling in conjunction with abnormal fault reports and notifications from condition monitoring.

**Statistics**
Statistical methods supplement the visual assessment of the data. An particularly important tool is the box plot visualizing locality, skewness, and spread of numerical data. The box itself plots 50% of the data spread around the median. Additionally, the whiskers indicate data outside the upper and lower quartiles. Discrete points are considered outliers [38].

### 3.2 Maintenance and Vehicle scheduling needs

The methods used to acquire knowledge in the area of maintenance resources and vehicle scheduling are majorly field research, interviews with staff as well as the literature research presented in the introduction.

Especially field research provides valuable insights on the daily business in the workshops. It raises awareness for the particular problems, needs, and discrepancies between instructions and actual processing of tasks. The field research is conducted by visiting the relevant servicing facilities and spectate the pertinent processes. Further, informal interviews with staff at the facility as well as maintenance disposition contemplate the impressions.

Due to the absence of field research the literature research, and interviews with staff from the vehicle scheduling are most relevant in determining their needs. A strict red thread for the latter is not required but prior definition of some general aspects to be addressed must be conducted.

### 3.3 Holistic framework

Subsequent processing of the emerging tasks could interfere with the holistic aim of this study or even deteriorate the results. Thus, it is of high relevance to simultaneously assess the vehicle data and needs, maintenance resources, and vehicle scheduling needs to facilitate balanced consideration.
Consequently, the framework on how equivalent conicity is embeddable to the wheelset maintenance strategy is established by demonstrating the work’s general execution. Note, that sectioning of the three main pillars is only supposed to improve readability and must not be understood as a chronological sequence.

### 3.3.1 Vehicle needs

To deduce vehicle specific needs a foundation with relevant knowledge must be build. Thus, an exhaustive technical analysis is conducted focusing on design aspects relevant to equivalent conicity which includes examining the bogie types, wheelset guidances, interfaces between bogie and carbody, wheelbase etc. Further, it is important to understand the differences among the vehicles. The relevant information is obtained from technical specifications and discussing certain aspects with experts. Experiencing and examining the vehicles and measurement devices in the field contemplates the comprehension.

### Data research

After establishing an in depth understanding for the vehicle’s and measurement device’s fundamentals, the work is continued with data analysis. Therefore, the wheel profile records are processed by the analysis software MATLAB. There, the data is first superficially aggregated and filtered into individual, small chunks and varyingly plotted to establish a feeling for the prevailing data. As a consequence, it is found that in the specific case MATLAB is suboptimal. As discussed in Section 3.1.5.1, the software unfolds its potential to the fullest when dealing with homogeneous numerical data. However, the data dealt with is highly heterogeneous due to numeric measurements as well as texts concerning workshop, wheelset type etc. As a result, the filtering procedures require extensive data type conditioning. In retrospect, a software more suited to processing heterogeneous data is recommendable.

Thereafter, the program is continuously expanded with functions aggregating and filtering the data according to the tree-like analysis approach shown in Figure 3.4. As introduced in 3.1.5.2, scatter and line plot functions set the foundation for assessment of different combinations of all relevant records and parameters. The histogram function in turn is vastly applied to $NP$ and $NP^2$ over equivalent conicity at 3 mm and 2 mm lateral wheelset displacement. Further, statistic functions such as polynomial fits, box plots, and linear regression models are implemented and evaluated on sensibility whereof box
plots and mean values generate the most value in the specific case.

In the early phases, extensive query of user input - so called soft coding - benefits comprehension of the prevailing data as the user can vastly influence the program’s tasks. Once profound understanding is established, more rigid routines are programmed - so called hard coding - in order to facilitate more reasonable computation times.

Consequently, the data is processed with the program as follows:

1. Assessment of differences in equivalent conicity behavior at varying lateral wheelset displacements as well as between data groupings according to Figure 3.4. Further, evaluation of individual behavioral aspects. This is majorly conducted by plotting different configurations of data clouds.
2. Evaluation of the general behavioral aspects of $NP$ and $NP_2$ by using scatter plots as well as histograms.

The records from fault reports and condition monitoring, exported from ERP, respectively RDS, generally feature highly heterogeneous data as well. However, for these records the challenge is to process them in terms of relevance, thus demanding a lot of manual assessment and direct interaction with the entries. As a consequence, EXCEL is beneficial in processing this data. However, the assessment of these records demands simultaneous consideration of the data processed in the MATLAB program as well. The respective evaluation builds upon four parts:

1. Investigation of abnormal stability cases, indicated by the ERP and RDS data, by individually line plotting equivalent conicities at all major lateral wheelset displacements as well as $NP$ and $NP_2$ over kilometers since last re-profiling. The assessment of these plots is conducted predominantly manually due to the pronounced scattering of the prevailing data, particularly at smaller lateral wheelset displacements.
2. Compilation of the data related to the abnormal line plots and application of statistic methods such as box plots to deduce more sophisticated warning limits. The governing heuristic of this task is individual assessment of every abnormal case and taking two stable equivalent conicity measurements closely before and after the initial warning was triggered. This manual method allows to account for scattering as well as exclusively including data points that are governing the transition to instability. Assessing the potential of the deductible equivalent conicity thresholds, for example by referring to the median,
is achieved by superimposing them into the respective general scatter plots. Additionally, the potential limits are deduced with respect to mileage facilitating assessment as a constant as well as a distance depending threshold.

3. Evaluation of the average speeds and speed ranges that result in instability. As a consequence, correlations between equivalent conicity limits and operating speeds can be deduced.

4. Assessment of statistical aspects concerning the fault reports by comparing the ratios of different events triggering re-profiling as well as the number of machined wheelsets.

Supplementary, interviews, for example with a train driver of the RABe 501, qualitatively support assessment of the stability issues’ relevance:

- How often does on-board staff experience warnings from the stability supervision?
- What consequences emerge from the stability warnings?

### 3.3.2 Maintenance resources

Similar to the basic vehicle needs, the fundamental maintenance resources are firstly researched by literature and refined with operator’s internal instructions.

**Field research and Interviews**

With formal comprehension being established field research at the bogie competence center (Basel) contemplates the understanding as procedures and tasks can be monitored and evaluated first hand. To build up an all-encompassing understanding many maintenance activities such as checking for cracks in the hollow shaft and refurbishments of larger components are investigated but particular focus is set on the procedures governing the wheel re-profiling. Thus, machining of the RABe 501 is closely investigated focusing on how many and what resources are required and how planning is conducted. Due to the nature of the component based servicing strategy applied by SBB activities like these are not necessarily processed simultaneously but synergies are exploited if possible.

Additional details are discovered by casually interviewing staff working at the vehicle as well as the maintenance disposition and addressing three major questions:
• What remaining kilometers before re-profiling are required to optimally plan the workshop resources?
• What are the specific challenges when maintaining EMUs and single passenger coaches?
• What are needs and problems that are not adequately addressed by now?

3.3.3 Vehicle scheduling needs

Railway specific literature on the vehicle scheduling needs is sparse. Thus, it is important to expand the research on papers examining needs from other modes of transport and draw correlations between certain aspects.

Interviews

Yet, some aspects addressing highly operator specific demands are not derivable from literature. Thus, they must be examined by interviewing the responsible staff such as train drivers and dispatchers. In the given case, challenges emerging from certain restrictions on the vehicle’s operability are addressed:

• What are the specific implications on operation if real-time events occur?
• What are the implications if the maximum speed of the RABe 501 is temporary limited?
Chapter 4

Results and Discussion

In the following, the study’s findings with particular focus on the RABe 501, supported by the EW IV and IC 2000 are presented. Section 4.1 elaborates the results individually for each main pillar followed by Section 4.2 where they are embedded to holistic strategies. The chapter is concluded by discussing the findings and strategies in Section 4.3.

To improve comprehension, equivalent conicities are further abbreviated with $\lambda_{eq}$, $\lambda_1$, $\lambda_2$, $\lambda_3$, and $\lambda_4$. The index denotes the respective lateral wheelset displacement in mm.

4.1 Individual results

The individual results establish the foundation in order to understand what superimposing a holistic framework means to the relevance of certain findings.

4.1.1 Vehicle needs

Usually, EN 14363 Appendix P governs the choice of the relevant lateral wheelset displacement $y$ for computation of equivalent conicity. The formula considers track gauge $TG$ and wheel gauge $SR$ as

\[ y = 3 \; mm, \text{ if } (TG - SR) \geq 7 \; mm. \]  

(4.1)

For the RABe 501 this explicitly yields 15 mm as $TG$ is set 1435 mm and $SR$ is set 1420 mm. Similar results are obtained for the EW IV and IC 2000 meaning that $y$=3 mm can be considered the relevant lateral wheelset displacement according to the norm. However, this heuristic is questioned if it is sufficient in the context of maintenance. Thus, the plots presented
in Figure 4.1 print $\lambda_1$ and $\lambda_3$ over kilometers since last re-profiling for the compiled wheelsets of the RABe 501, EW IV, and IC 2000. It can be seen that for the RABe 501 equivalent conicity generally grows faster at smaller lateral wheelset displacements but is prone to scattering. Due to the pronounced scattering of $\lambda_1$ experienced at the EW IV and IC 2000, assessment of differences is prohibited. Generally, scattering decreases drastically with increasing lateral wheelset displacement for all vehicles.

Another finding from Figure 4.1 are the differences in equivalent conicity’s behavioral schemes. For the EW IV and IC 2000 equivalent conicity starts at very low magnitudes and grows immediately with degressive tendency. After a certain mileage it approaches a plateau and subsequently stays constant. A similar behavior can be perceived from Intercity-Express (ICE) 3 trains with special wheel profiles operated by DB in Germany, as shown in Figure 4.2. In contrast, equivalent conicity of the RABe 501 starts at higher initial...
magnitudes and stays relatively constant for certain mileages. Subsequently, it grows progressive without approaching a plateau.

Investigation of differences between specific bogie and wheelset types is solely relevant to the RABe 501 as it is the only vehicle in this study featuring various types. Figure 4.3 plots $\lambda_3$ over kilometers since last re-profiling for the LUB as well as the JUB compiled with the JPB. It can be perceived that equivalent conicity grows fastest at the LUB with a maximal difference in the order of 50,000 km before the alarm limit is approached. Refinements in comparing and grouping beyond the bogie groups do not reveal significant deviations or amendments to this finding. Thus, they are not further addressed.

To further comprehend the previous results the $NP$ as well as $NP2$ are introduced. The latter aims on supporting the assessment of the equivalent conicity properties closer to the equilibrium and is an adaption of the $NP$ describing the gradient between equivalent conicity at 3 mm and 1 mm as

$$NP2 = \frac{\lambda_3 - \lambda_1}{2}.$$ (4.2)
Figure 4.4 plots $NP$ and $NP^2$ of the RABe 501, and $NP$ of the EW IV over kilometers since last re-profiling as well as over $\lambda_3$, respectively $\lambda_2$. Generally, literature expects $NP$ to decrease with mileage [13]. Presumably, $NP^2$ acts similar. These expectations generally hold true but for the EW IV the plots additionally underline the attainment of a stable dimension by approaching a constant negative value. For the RABe 501 in contrast, $NP$ and $NP^2$ do not approach a constant section. Furthermore, $NP^2$ scatters notably due to the influence of $\lambda_1$.

Additionally, histograms can be used to support the evaluation of $NP$ and $NP^2$ plotted over the respective equivalent conicity. Figure 4.5c shows that the EW IV has a similarly high data density over a large area. Particularly the dense area at lower magnitudes of $NP$ indicates the equivalent conicity at which the profile approaches its stable dimension. In contrast, the RABe 501 shows solely decreasing data density outside the re-profiled condition which
is shown in Figure 4.5a for $NP$ and Figure 4.5b for $NP_2$.

(a) $NP$ over $\lambda_3$ data density RABe 501  
(b) $NP_2$ over $\lambda_2$ data density RABe 501  
(c) $NP$ over $\lambda_3$ data density EW IV

Figure 4.5: Data density of $NP$, $NP_2$ of the RABe 501, $NP$ of the EW IV

**Validity analysis**

The described phenomena can be validated to a large extend by the differing wheel profiles applied to the RABe 501, EW IV, and IC 2000. While the passenger coaches use S1002 wheel profiles, the RABe 501 uses EPS wheel profiles. Research from [12, 14] shows that the EPS wheel profile has a high CCI when being paired with the Swiss network properties meaning that the density of contact points within a small bandwidth on the tread is very high. As a result, these papers argue that it cannot achieve a stable dimension, thus does not approach an equivalent conicity plateau. Consequently, $NP$ and $NP_2$ cannot approach a stable section either. In contrast, the S1002 wheel profile adapts well to Swiss network properties enabling a stable dimension.

The earlier growth of equivalent conicity from the RABe 501 at smaller lateral wheelset displacements is linkable to the high CCI as well. This is validated by the predominant application of the EMU on rather straight track matching the CCI’s calculation assumptions. Furthermore, majorly impacted by the HALL, the wheel gauge increases with mileage. Thus, the magnitude of Equation (4.1) decreases indicating an increasing relevance of smaller lateral wheelset displacements. These aspects suggest that predominantly monitoring $\lambda_3$ as well as applying one identical warning limit to all equivalent conicities
may be insufficient for establishing more sophisticated maintenance strategies.

The faster grow of equivalent conicity at the LUB of the RABe 501 can generally be validated by the bogie’s relevance in steering the EMU. It is further impacted by differing design aspects compared to the other bogies such as the four yaw dampers connected to solely one carbody.

The aforementioned validations are restricted to Switzerland. For example in Italy the phenomena are - to a certain extend - vice versa. There, 1:20 rail inclination is widely applied which generally suits the EPS profile better and might enable a stable dimension. However, as of now, the relevance of considering the networks outside of Switzerland is neglectable as less than 25% of the RABe 501 main network are within Italy, while more than 75% are Swiss network and no other country is currently operated by the EMU. Yet, Germany is expected to be included at a later point meaning similar considerations to Italy.

To conclude, the findings indicate that the EW IV coaches are rather wear and equivalent conicity friendly. This can be validated by comparing the number of fault reports with the IC 2000 showing that in 2021 they had 1.6 times more general as well as stability related fault reports per car than the EW IV. Also the mean mileage between re-profiling validates this with the EW IV achieving 311,000 km, the IC 2000 246,000 km and the RABe 501 only 190,000 km on the UBs and 201,000 km on the powered bogie, TDGs (PBs).

### 4.1.2 Maintenance resources

Maintenance planning is challenged to distribute the available resources concerning staff as well as machinery evenly. This is particularly difficult with the component based strategy of SBB as trains tend to be more frequently and shorter in the workshop.

As a result, disposition must know a trains appearance well in advance. Considering the fact, that vehicles may have mileages >1000 km a day and distance data being processed with one day delay remaining kilometers until action must be deduced thoroughly. From interviews it is known that the commonly settled 20,000 km are just about enough but more severe faults may result in even shorter distances. Thus, maintenance planning stresses the need of sufficient lead times and as few shortened intervals as possible.

Equally important to the scheduling of the time slot are the assigned
resources. Depending on experience one or two workers are required to machine the wheels. The lead times per UB as well as PB of the RABe 501 are identical with 1 hour each. Consequently, the time required to re-profile all 48 wheels of the EMU is 12 hours. Additionally, preprocessing and postprocessing may take up to 10 hours. Summed up, complete machining of the RABe 501 might occupy up to two workers from three shifts each. Furthermore, EMUs are not sensibly separatable meaning that the unit must be dragged bogie by bogie over the re-profiling machinery. Thus, the track must offer the unit's length before and after the tool yielding about 400 m.

The absence of an established re-profiling strategy for the RABe 501 further aggravates the planning. As of now, the number of axles to be machined is decided on a case by case principle. This leads into significant inconsistencies indicated by the statistics: In 2021 61 RABe 501 were machined of which five had all wheels re-profiled, while in 2022 47 RABe 501 were machined of which 20 had all wheels re-profiled.

Further, the relevance of machining causes must be known in order to properly assess potential strategies: In 2021 and 2022 more than 60% of the initial re-profiling registrations were due to tread defects, while about 15% were due to stability issues. Only one machining in 2021 as well as 2022 was triggered by transgression of flange limits. Theoretically, the flange wear would allow for significantly longer mileages than currently achieved. The remaining cases were caused by mixed or other reasons.

**Validity analysis**

The findings presented hold valid for SBB as they are majorly derived from internal field research and interviews with staff. However, it is expected that similar aspects apply to other railway operators as well.

Furthermore, a significant gap from the status quo in rail vehicle maintenance to concepts from literature is explored. While the general needs obviously demand a higher degree of stability and predictability, respective concepts are yet to be extensively applied and applications of IoT principles are almost nonexistent.

### 4.1.3 Vehicle scheduling needs

The issue of a short amount of remaining kilometers, as elaborated in Section 4.1.2, is also relevant to vehicle scheduling. On the one hand, the vehicle must be excluded and replaced in the WTT. On the other hand, the
vehicle’s transfer trip to the facility has to be scheduled while avoiding empty runs and implications on the timetable as much as possible. As a result, planned servicing time slots or at least a large amount of remaining kilometers until action are demanded.

However, short term, respectively real-time events such as vehicle breakdowns, speed reductions etc. are even more challenging. The fact that suspending EMUs like the RABe 501 inevitably concerns the whole unit aggravates the handling of these events even further. To deal with these situations research such as [29] investigates FMS real-time decision making which provides vehicle scheduling with a potential handling. However, the general requirement imposed on a maintenance strategy is still to experience as few real-time events as possible.

Validity analysis
The presented results are majorly derived from literature providing a very general overview on demands imposed by the vehicle scheduling. However, they obviously emphasize that the most relevant hurdle are real-time events. This finding is validated by interviewing staff from SBB such as train drivers. Furthermore, the interviews once again indicate the need for more predictive suspending of vehicles and demand the limitation of (unexpected) operational restrictions as much as possible.

4.2 Holistic results
Warning limits are commonly used in railway maintenance due to their attractiveness in assessing the condition of components rather simple and enabling restricted predictability. As of now, the thresholds are often derived from homologation, infrastructure limitations, manufacturer requirements and experience. Evaluation of correlations between behavioral aspects and design features as well as operational aspects tends to be solely rudimentary.

For the SBB RABe 501 the currently used limits of equivalent conicity, 0.35 and 0.4, are derived from experience and network homologation respectively. They are identically applied to $\lambda_1$, $\lambda_2$, $\lambda_3$, and $\lambda_4$ although solely $\lambda_3$ is specifically relevant to the homologation. Manually assessed transgression of these limits or abnormal behavior triggers the derivation of usually 20,000 remaining kilometers until re-profiling. The number of wheels being re-profiled is decided on a case by case principle. This strategy is denoted with roman I and called STATUS QUO.
4.2.1 Strategies

With the knowledge acquired from the individual results as well as auxiliary data from the fault reports (ERP) and condition monitoring (RDS) alternative strategies can be proposed for the RABe 501.

Uniformly applicable to all following strategies are the very limited differences in equivalent conicity behavior between varying bogie types. Thus, all proposed strategies suggest machining all 24 wheelsets if maintenance is conducted due to stability, respectively equivalent conicity issues and if a sensible mileage in the order of >150,000 km is achieved.

Strategy roman II called RDS-LIMIT refers to the same principles as I but proposes more sophisticated, sectional warning limits that enable indirect checking for the expected $\lambda_{eq}$ function contour (see Figure 2.2b). Fundamental to the derivation of the improved thresholds are abnormal stability cases indicated by the RDS records. Figure 4.6a and 4.6b superpose the equivalent conicities of the abnormal cases with the general data clouds. The exact heuristic behind these points was elaborated in Section 3.3.1. A similarly progressive tendency as well as localization along the upper edge of the data cloud can already be perceived visually.

Figure 4.6: Abnormal stability cases indicated by RDS for the RABe 501

The box plots presented in Figure 4.6c and 4.6d further improve the
assessment by showing that the median, the upper and lower quartile as well as the scattering decrease with increasing lateral wheelset displacement. Furthermore, almost 75% of the initial warnings are triggered after 250,000 km. Consequently, the medians are taken as initial reference for sectionally constant limits. Resultingly, this yields the thresholds for strategy $\lambda_1 = 0.42$, $\lambda_2 = 0.38$, $\lambda_3 = 0.35$, and $\lambda_4 = 0.32$. They are indicated in Figure 4.6a and 4.6b by bold green dashed lines. It is recommended to apply all of them but majorly assess the rather stable records of $\lambda_2$ and $\lambda_3$. Considering the new warning limits at least 20,000 km are reasonable and reliable before interference with the homologation limit must be feared.

The predictability can be further improved by integrating auxiliary meta data from RDS. In 2022 and early 2023 a total of 314 stability related notifications hold information at which speed a warning was triggered. 288 occurred at velocities above 215 km/h. Thus, the thresholds proposed in strategy II can also be related to a restriction on operational speeds $>215$ km/h. As a matter of fact, in Switzerland the RABe 501 is only allowed to exceed 200 km/h in the Gotthard base tunnel under exceptional circumstances meaning limited operational relevance of the design speed. After capping the operational velocity the subsequent thresholds are the limits from strategy I followed by the derivation of 20,000 remaining kilometers. As a result, the EMU may be able to operate significantly longer within one re-profiling interval. Roman III denotes this potential strategy called RDS-LIMIT+215.

Roman IV introduces the strategy called PROGNOSIS. There, a linear regression model can be either referred to the thresholds from strategy I or strategy II. As a result, the mileage until transgression of the limits can be predicted and intervention be planned well in advance.

Considering the limited influence of stability issues on the number of initial registrations to wheel re-profiling as elaborated in Section 4.1.2, the current mean mileages discussed in Section 4.1.1, and the potentially achievable mileages due to stability presented in box plot 4.6c, a fifth strategy denoted roman V can be added. It proposes no explicit implementation of equivalent conicity to the maintenance strategy and is called NOTHING.

The last strategy is denoted VI and called PREVENTIVE. It proposes to re-profile all wheels after a fixed distance. Based on Figure 4.6d the target is recommended at 225,000 km to intercept 75% of the stability issues.
Validity Analysis
The prevailing abnormal data points indicated by RDS would allow for derivation of distance depending as well as constant warning limits. However, knowing that most units manage a sufficient mileage before triggering the initial warning, and that a distance depending line fit would cover barely more abnormal cases but aggravate the processing, validates the choice of constant warning limits.

Yet, the thresholds must consider the lateral wheelset displacements validating the sectional limits. The proposition of $\lambda_2$, and $\lambda_3$ as the main parameters for assessment is validatable as the former can substitute the supposingly important $\lambda_1$ enabling supervision of equivalent conicity relatively close to the equilibrium while scattering significantly less. Assessment of $\lambda_3$ in turn is demanded by the stability limits imposed from the homologation which refers to Equation (4.1).

Relying on the median for initial deduction of the improved thresholds is validated by the fact that the lower quartile would indicate too many records as abnormal while the upper quartile might indicate abnormal cases too late. However, after a testing phase the derivation of final thresholds might require iteration anyway.

Waiving differentiation of bogie types is validated by three aspects. First, even the most sensitive equivalent conicity of the LUB usually achieves sufficient mileages before approaching a limit. Second, with the commonly applied 20,000 remaining kilometers before action the actual difference between necessary consideration of differing bogie types is reduced to 30,000 km. Assuming common mileages this means only about 3 weeks in-between the first re-profiling and the indication of the next required action. Third, the stability warnings from RDS do not indicate dependency on a specific bogie type either.

Strategy IV, PROGNOSIS is only addressed superficially in this study. Due to the available data density and quality as well as a lack of data at higher mileages it is assumed that implementation requires substantial efforts in training and verifying a models reliable predictability.

Strategy V, NOTHING suffers from a lack of compliance concerning the homologation. Thus, some fundamental equivalent conicity supervision has to be taken into account leading the strategy partly ad absurdum.
Last but not least, strategy **VI. PREVENTIVE** is a well known approach but yields rather conservative measures while holding some risks such as unnoticed equivalent conicity issues after short mileages as well as restricted homologation concurrence. Consequently, it does not sufficiently meet the study’s goal of proposing a more sophisticated maintenance strategy.

### 4.3 Discussion

The presented vehicle focused results enable improved understanding for equivalent conicity’s behavior, trends, correlations etc. As a result, many new opportunities that potentially sophisticate wheel re-profiling strategies are introduced. However, embedding the individual results into more holistic wheel re-profiling strategies for the RABe 501 yields notable rationalization.

Although grouping of bogies might prolong a wheelset’s lifecycle, it is found that the differences are insignificant in the context of requisitions from the maintenance resources and vehicle scheduling.

Furthermore, no sensible application of $NP$ and $NP2$ to the condition assessment of wheels is deductible. They generally reaffirm the findings but do not unearth significant new results relevant to maintenance considerations. As an example, oscillation of $NP$ and $NP2$ plotted over mileage around 0 is found an indicator of stability issues with $NP2$ being slightly more relevant for the given case. However, no quantitative conclusion can be drawn that this heuristic is reliable enough for assessing the wheelset’s stability, and equivalent conicity condition.

The needs from maintenance as well as vehicle scheduling draw a strong demand towards improved and more stable predictability. Further, a strategy is supposed to be well comprehensible and complete to ensure reliable planning of the required resources.

Consequently, most strategies proposed in Section 4.2.1 build upon a similar heuristic as already established but integrate more sophisticated aspects from the vehicle’s individual findings. Incorporating the data from the on-board condition monitoring in the deduction of warning limits improves the meaningfulness, and resulting predictability significantly. Further, it allows for derivation of more relevant consequences when a limit is approached.
### 4.3.1 Strategy assessment

Table 4.1 quantitates the potential of the six strategies in terms of coherence with specific needs imposed from the three main pillars as well as the embeddability. The assessed requirements are predominantly derived from the individual results and specifically tailored for demands from SBB. It is important to understand, that most of them are rated fully self-sufficient as if there are no other sources of interference than equivalent conicity, respectively stability. Thus, "Sensibility of the implementation" compares the strategies relevance to other influencing factors like tread defects. Yet, this embeddability requirement can only be interpreted as a superficial indicator of a strategy’s relevance.

#### Table 4.1: Ranking of the strategies I-VI

<table>
<thead>
<tr>
<th>Requirements</th>
<th>STATUS QUO</th>
<th>RDS-LIMIT</th>
<th>RDS-LIMIT+215</th>
<th>PROGNOSIS</th>
<th>NOTHING</th>
<th>PREVENTIVE</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Vehicle</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sufficient distance in between re-profiling</td>
<td>0</td>
<td>3/3</td>
<td>3/3</td>
<td>3/3</td>
<td>2/3</td>
<td>2/3</td>
</tr>
<tr>
<td>Sufficient distance in between wear changes</td>
<td>0</td>
<td>3/3</td>
<td>3/3</td>
<td>3/3</td>
<td>2/3</td>
<td>2/3</td>
</tr>
<tr>
<td>Limited influence on defect emergence</td>
<td>0</td>
<td>3/3</td>
<td>3/3</td>
<td>3/3</td>
<td>2/3</td>
<td>2/3</td>
</tr>
<tr>
<td>Limited demand on staff</td>
<td>0</td>
<td>3/3</td>
<td>3/3</td>
<td>3/3</td>
<td>2/3</td>
<td>2/3</td>
</tr>
<tr>
<td>Good traceability</td>
<td>0</td>
<td>3/3</td>
<td>3/3</td>
<td>3/3</td>
<td>2/3</td>
<td>2/3</td>
</tr>
<tr>
<td>Homologation concurrence</td>
<td>0</td>
<td>3/3</td>
<td>3/3</td>
<td>3/3</td>
<td>2/3</td>
<td>2/3</td>
</tr>
<tr>
<td><strong>Maintenance</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Derivation of remaining kilometers in addition</td>
<td>0</td>
<td>3/3</td>
<td>3/3</td>
<td>3/3</td>
<td>2/3</td>
<td>2/3</td>
</tr>
<tr>
<td>Few spontaneous interventions</td>
<td>0</td>
<td>3/3</td>
<td>3/3</td>
<td>3/3</td>
<td>2/3</td>
<td>2/3</td>
</tr>
<tr>
<td>Comprehensive tracking strategy</td>
<td>0</td>
<td>3/3</td>
<td>3/3</td>
<td>3/3</td>
<td>2/3</td>
<td>2/3</td>
</tr>
<tr>
<td><strong>Vehicle Scheduling</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Merging few spontaneous interventions</td>
<td>0</td>
<td>3/3</td>
<td>3/3</td>
<td>3/3</td>
<td>2/3</td>
<td>2/3</td>
</tr>
<tr>
<td>Sparing time planned maintenance time slots</td>
<td>0</td>
<td>3/3</td>
<td>3/3</td>
<td>3/3</td>
<td>2/3</td>
<td>2/3</td>
</tr>
<tr>
<td>Incorporation of customer inquiries</td>
<td>0</td>
<td>3/3</td>
<td>3/3</td>
<td>3/3</td>
<td>2/3</td>
<td>2/3</td>
</tr>
<tr>
<td>Short suspending durations</td>
<td>0</td>
<td>3/3</td>
<td>3/3</td>
<td>3/3</td>
<td>2/3</td>
<td>2/3</td>
</tr>
<tr>
<td>Limited impact on operation</td>
<td>0</td>
<td>3/3</td>
<td>3/3</td>
<td>3/3</td>
<td>2/3</td>
<td>2/3</td>
</tr>
<tr>
<td><strong>Embeddability</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Holism-Sum</td>
<td>-6 2/3</td>
<td>6 2/3</td>
<td>10</td>
<td>1/2</td>
<td>-6 5/6</td>
<td>-1 1/6</td>
</tr>
<tr>
<td><strong>Grand total</strong></td>
<td>3 1/3</td>
<td>11 2/3</td>
<td>0</td>
<td>1/2</td>
<td>3 1/6</td>
<td>6 1/3</td>
</tr>
</tbody>
</table>

To ensure equal balancing as well as limit the biases when filling in Table 4.1, each pillar has 10 points available. They are distributed evenly among all requirements, thus unweighted. The points are multiplied with -1 if the requirement is negatively impacted, 0 if it is not impacted or impact is unknown, and +1 if it is positively impacted.

In grand total strategy II comes out best and second if only the holistic pillars are considered. Strategy III leads the holism-sum but the complicate embeddability worsens its grand total. More detailed elaborations and argumentations on the presented scorings and results are provided in Appendix A.

The assessment is highly individual as it depends on requirements
specifically imposed by an operator as well as personal biases by the appraiser. Thus, the prevailing results can solely be interpreted as an indication for SBB on how to embed equivalent conicity to the wheelset maintenance strategy of the RABe 501 and as a general guideline on how other operators can assess the relevance of similar strategies.
Chapter 5
Conclusions and Future work

To wrap up the present study Section 5.1 reflects on the drawn results and supplementary insights. Section 5.2 discusses the limitations of this work. The paper is concluded with recommendations on future work presented in Section 5.3 and some general reflections in Section 5.4.

5.1 Conclusions

The importance of elaborate embedding of equivalent conicity to rail vehicle maintenance is caused by its increasing relevance in the homologation. Build upon the case of a Swiss EMU, the study constructs a framework to systemically process, analyze and assess concerning data while accounting for needs beyond the vehicle itself. This enables formulation of well balanced, holistic wheel re-profiling strategies.

Particularly strategy II, RDS-LIMIT and III, RDS-LIMIT+215 propose novel approaches that build upon in depth evaluation of data from multiple sources. The most elaborate strategy III comes out best for the holistic pillars but serious difficulties in embeddability yield a drop to the last spot while the less sophisticated strategy II takes the lead. This pictures the difficulty in introducing strategies that are optimal to all stakeholders as well as reasonably embeddable.

The almost self-sufficient nature of the ranking must be considered as well. From the findings in Section 4.1.2 it is known that for the RABe 501 tread defects are prevalent in triggering re-profiling activities. Furthermore, stability issues predominantly occur at very high speeds >215 km/h. Thus, the actual relevance of a strategy must be thoroughly verified.

It is also found that several individual findings are not explicitly relevant to
maintenance considerations. On the one hand, maintenance has only limited influence on a train’s technical design and on the other hand, more elaborate strategies suffer from difficulties in embeddability and practicality. Yet, the in depth understanding for equivalent conicity established by the individual findings is inevitable in order to derive more sophisticated strategies.

To sum up, primarily proposing strategy II, RDS-LIMIT is sensible in the given case. Improvements to the status quo are obvious due to reduced dependency on dedicated experts, compliance with homologation, sufficient predictability for maintenance scheduling as well as resource planing, and limited impact on operation. Furthermore, no pillar is particularly disadvantaged and implementation is rather simple. The sensibility of embedding compared to other influencing factors can be considered neutral meaning that it may be fairly relevant in daily operation.

5.2 Limitations

Due to the nature of a case study as well as other aspects, the results and findings hold some limitations.

First, the data analysis might not unfold its potential to the fullest. From papers such as [39] it is known, that smarter maintenance requires many sensors to record enough relevant data. The RABe 501 generally features an adequate data basis from stationary as well as on-board equipment but the records tend to be insufficiently incorporated to IoT principles which is essential [24]. As of now, three independent databases coexist in the given case demanding extensive preparatory efforts before the data can actually be analyzed. Furthermore, the quality of data differs between databases as well as within the same records. For example different measurement devices yield variant scattering for the same parameter. Resultingly, the possibilities in data processing, evaluation, and predictability are partly restricted.

Second, stability issues indicated by RDS notifications cannot differ between track irregularities and deteriorated wheel profiles. As a result, the equivalent conicities computed in C2M and linked to RDS warnings must be understood as a substitute of probably much higher values at the routes where issues occurred. In some cases the notifications might even wrongfully indicate a deteriorated wheel profile due to abnormal track specifics.
Third and last, the results of the case study cannot directly be transferred to other applications. Design and operational features as well as specific needs of affected sub-areas may vary substantially. The latter strongly depend on the general maintenance philosophy as well as the operator’s size, countries of operation, available resources etc. Thus, the present work must be understood as a general framework rather than a specific instruction.

5.3 Future work

The general framework on how equivalent conicity is embeddable to the wheelset maintenance strategy can be considered rather complete. However, some details are still matter to future work.

5.3.1 Next steps

First, to extract the added value from the present study, some complementary steps must be taken to ensure beneficial implementation.

Strategy assessment
The work does not explicitly account for monetary aspects. Although the proposed strategies indicate cost benefits they are yet to be seriously evaluated. Economic aspects could also play an essential role in properly weighting the requirements from Table 4.1.

Complementary, final assessment of potential strategies must always be conducted with experts from the affected sub-areas. The single assessment applied to this work generally suffers from bias as well as a potential lack of understanding for specifics.

Consequently, it is strongly suggested to reassess the proposed strategies with experts as well as by taking economic and further operator specific aspects into consideration.

Subsequently to deciding on a strategy, the actual applicability of the new thresholds as well as the sensibility of the proposed consequences must be evaluated. Thus, the implementation phase must be closely supervised by the operator and potential flaws be revised.

Data processing
A highly relevant background task to be conducted is purposeful concatenation and processing of the coexistent databases. On the one hand, this demands a
certain quality of data recording such as standardized entries for fault reports. On the other hand, the databases require standardized interfaces such as the full UIC train numbers to ease concatenation of the data.

### 5.3.2 Research gaps

Second, aspects that are still matter to research are pointed out. They are not exclusively connected to the study’s main field of research as some side findings are made as well.

**Generality**

Foremost, the presented framework must be verified beyond the given case on its generality. Other applications may have a different quality of data available, require other tools such as linear regression models, or vary in terms of imposed demands. Consequently, the degree of coherence can be assessed and potential flaws to its generality be revised.

**Wheel-rail contact geometry**

Supplementary to this study, it was found that the established wheel profiles in Switzerland, S1002 and EPS, paired with the prevalent track design may be suboptimal. Among others, the choice of the wheel profile depends on requirements imposed by the national legislation, operated foreign countries, vibration excitation of the carbody, and experience. However, no matter which established profile is chosen significant drawbacks emerge such as early or increasing stability issues, low frequency carbody excitations, pronounced rolling contact fatigue, uneven wear etc. Thus, opportunities to optimize the Swiss network specific wheel-rail contact properties should be investigated.

### 5.4 Reflections

As part of the stability assessment in EN 14363 more and more network homologations refer to equivalent conicity as a relevant indicator on a vehicle’s hunting motion. They specify fixed limits that the operators must adhere to. Thus, more sophisticated handling of the parameter in wheelset maintenance is inevitable.

The presented findings may also be relevant upon maintenance as the planned expansion of operation of the RABe 501 to Germany might lead to regular runs at 250 km/h which demands understanding of the underlying stability phenomena. However, the knowledge established can only be
Conclusions and Future work

partially transferred since Germany uses a different track specification.

To conclude, this study enables operators to effectively deal with the increasing relevance of equivalent conicity as a condition parameter in rail vehicle maintenance. It further shows that the scope in order to be compliant with homologation is yet to be fully explored.

The study also holds high relevance from a societal point of view. Operators can only provide reliable services to the customer if they are able to adapt well in time to changing, respectively increasing requirements. This demands consequent and continuous improvement of their operational standards of which maintenance is an inevitable part of.
Conclusions and Future work
References


Appendix A

Pros and Cons of the strategies

As a matter of fact, the assessment of the proposed strategies is highly individual. It depends on the specific requirements imposed by the operator, the appraiser(s) filling Table 4.1 as well as the weighting of certain requirements. For the given case, the available points were distributed evenly among the pillars and weighting of requirements was waived to ensure a limited impact of biases.

Table A.1 presents detailed argumentations concerning the scoring applied to Table 4.1. Pros are rated +1 for the respective requirement, Cons -1, and Risks 0 or -1. Furthermore, some requirements cannot be assessed with the prevailing knowledge, thus they are not discussed in Table A.1 and rated 0 in Table 4.1. The coloring scheme indicates the argument’s related pillar. Uncolored statements are supplementary. Note, that the table’s arguments are not claiming unimpeachability but shall ensure traceability of the drawn results.

Table A.1: Discussion of Pros and Cons concerning Table 4.1
<table>
<thead>
<tr>
<th>Strat.</th>
<th>Description</th>
<th>Pros</th>
<th>Cons</th>
<th>Risks</th>
<th>Notes</th>
</tr>
</thead>
</table>
| I     | STATUS QUO | Manuel assessment + X remaining km + Re-profile X wheelsets | • Considers homologation limit  
• Due to the experience from the expert assessing equivalent conicity, customer inquiries can be handled easily  
• Well established strategy that can be continued without additional efforts  
• Complementary to other types of defects and issues | Engineering experts needed to assess the data  
• No clear guidelines and methods, thus limited traceability  
• Re-profiling strategy is decided case by case | Absence of experts interrupts assessment  
• Misinterpretation or missing on problems  
  o Shortened remaining km  
  o Spontaneous intervention | On-board stability supervision supports strategy |
| II    | RDS-LIMIT  | RDS-Limits + Fixed remaining km + Re-profile 24 wheelsets | • Clear guidelines and methods, thus good traceability  
• Similar/Below homologation limit  
• Remaining km >= 20,000 possible  
• Limited risk of spontaneous intervention due to reduced probability of on-board diagnosis interference  
• Re-profiling all wheelsets simplifies the machining strategy  
• No restrictions on operation due to reduced probability of on-board diagnosis interference  
• Similar to strategy 1, thus easy to implement | Conservative, thus the mileages are potentially reduced  
• Every re-profiling activity takes maximally long and requires a maximum of resources  
• Planned maintenance slots are not strictly adhered to  
• Train is suspended maximally long | No explicit experts that might be able to handle abnormal cases  
• Relevance compared to other influencing factors such as tread defects not obvious  
• Missing out on critical cases that are unrelated to the warning limits | On-board stability supervision partly bypassed |
| III   | RDS-LIMIT+215 | RDS-Limits + 215 km/h limitation + Homologation limit | • Stepwise method yields maximal mileage before re-profiling  
• Clear guidelines and methods, thus good traceability | Every re-profiling activity takes maximally long and requires a maximum of resources | No explicit experts that might be able to handle abnormal cases | On-board stability supervision |
### IV PROGNOSIS

**Stability prognosis with RDS-Limits + Re-profile 24 wheelsets**

- (Almost) No engineering staff required
- Remaining km $\geq 20,000$ as well as limited spontaneous events possible as RDS-Limits are the threshold
- Re-profiling all wheelsets simplifies the machining strategy
- Well in advance planned maintenance slots due to prognosis

- Considers homologation limit
- High kilometers until re-profiling as vehicle may be registered when approaching the RDS-Limit
- Re-profiling all wheelsets simplifies the machining strategy
- Fixed speed reduction limits risk of spontaneous on-board diagnosis speed reduction
- Few spontaneous events impacting operation due to low risk of diagnosis interference
- Well planned maintenance slots due to high kilometers until re-profiling

- Train is suspended maximally long
- Starting with the RDS-Limit operation is restricted to 215 km/h
- Relevant in terms of delays at the Gotthard base tunnel
- Tough to implement as many players are included:
  - Engineering
  - Dispatcher
  - Timetabling staff

- Mileages would be well above the currently reachable mileages which are limited by other influencing factors such as tread defects
- Missing out on critical cases that are unrelated to the warning limits
- Limited traceability
- Prognosis might be wrong, thus, interfering with the homologation limit
- Prognosis might be wrong leading in potential spontaneous events
- Risk of spontaneous events impacting operation
- Limited understanding of the actual equivalent conicity if engineers solely rely on the prognosis
- Demand on implementation difficult to assess

- Actual quality of this method strongly depends on stability of the measurements in terms of scattering and data density as well as analyzed lateral wheelset displacement
- On-board stability supervision

(partly bypassed)

How to inform the train driver?
### V

**NOTHING**

- 'No' implementation
  - + Re-profile 24 wheelsets

<table>
<thead>
<tr>
<th></th>
<th>Theoretically unlimited mileage</th>
<th>(Almost) No engineering staff required</th>
<th>No impact on derivation of remaining kilometers</th>
<th>Implementation right away possible</th>
<th>At the moment, due to the significance of tread defects, this strategy might be considerable</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th></th>
<th>No understanding for equivalent conicity behavior</th>
<th>Spontaneous interventions by on-board diagnosis likely</th>
<th>No re-profiling strategy:</th>
<th>Partial re-profiling might lead into frequent re-suspending to re-profile other wheels with on-going risk of diagnosis intervention</th>
<th>Spontaneous diagnosis intervention leading in operation restrictions likely</th>
<th>No experts that can handle extraordinary events</th>
</tr>
</thead>
</table>

- Homologation conformity unclear. An expert might be still needed to assess abnormal cases or watch out for transgression of some specific limits, making it similar to strategy I
  - Benefits on plannability unclear as on-board diagnosis might interfere

- On-board stability supervision highly relevant

- Data density at higher mileages might be too limited
- Measurement density might be too low
- Scattering, explicitly at certain lateral wheelset displacements, might be difficult to handle
- Relevance compared to other influencing factors such as tread defects not obvious
- Missing out on critical cases

- Supports strategy
<table>
<thead>
<tr>
<th>VI PREVENTIVE</th>
<th>Fixed mileage: 150,000 – 225,000 km + Re-profile 24 wheelsets</th>
</tr>
</thead>
</table>
|               | • (Almost) No engineering staff required  
• Mileage and remaining kilometers until re-profiling are the same  
• Re-profiling all wheelsets simplifies the machining strategy  
• Well planned maintenance slots due to high kilometers until re-profiling |
|               | • Short mileages in-between re-profiling to intercept risk of stability issues  
• No understanding for equivalent conicity behavior and limited traceability  
• Every re-profiling activity takes maximally long and requires a maximum of resources  
• Train is suspended maximally long |
|               | • Maybe not fully homologation compliant  
• Spontaneous intervention might occur as there is no real-time supervision of equivalent conicity  
• Risks of spontaneous events due to diagnosis interference  
• Limited understanding of the actual equivalent conicity behavior if engineers solely rely on the fixed mileage |
|               | • On-board stability supervision highly relevant |
Appendix A: Pros and Cons of the strategies
With continuing digitization of railways an increasing number of data is recorded but particularly in operation advanced analysis tends to be partially rudimentary. Yet, it is essential to implement sophisticated processing for all records in order to develop more purposeful and predictive vehicle maintenance strategies that adhere to the increasing requirements imposed by the homologation. Typically developing requisites are permissible track forces and lateral accelerations which are directly affected by the vehicle’s condition. The present work addresses this issue by executing a case study focused on a Swiss high-speed electric multiple unit with equivalent conicity being the main parameter of interest. This geometry quantity holds high relevance in determining the running stability of track guided vehicles, respectively in assessment of comfortable and safe operation. Currently, it experiences an increasing significance in the homologation as well. Thus, wheelset maintenance is challenged to elaborately embed equivalent conicity to the other influencing factors in the re-profiling strategy.

A framework is established on how operational data can be analyzed and findings systematically be evaluated. The required records are provided by a Swiss railway operator and majorly processed by visualization as well as statistic tools while considering vehicle design and operational aspects. The subsequent proposition of strategies is accompanied by holistic balancing of vehicle needs, maintenance resources, and vehicle scheduling needs.

As a result, correlations concerning the vehicle’s configuration, design, and operational properties are observed. Incorporating these observations, for example by applying advanced warning limits, enables deduction of more predictive and holistic strategies. The potentially emerging benefits
are manifold and range from lower demand on engineering staff, increased mileages, to fewer unplanned servicing tasks and subsequently increased operational stability. Further, the findings emphasize the need of in depth understanding about relevant data to derive more advanced and holistic maintenance strategies.

**Abstract[ger]**: Eisenbahnbetrieb, Äquivalente Konizität, Radsatzinstandhaltung, Intelligente Instandhaltungsstrategien, Datenanalyse

**Abstract[swe]**: Järnvägsdrift, Ekvivalent Konicitet, Hjulset Underhåll, Smart Underhåll, Dataanalys

**Abstract[eng]**: Railway Operation, Equivalent Conicity, Wheelset Maintenance, Smart Maintenance, Data Analysis


Som ett resultat av detta observeras korrelationer mellan fordonens tekniska egenskaper med design- och driftsegenskaper. Genom att inkludera genetiska utvärdering av behov för såväl fordon och underhållsanläggningar och fokuserade strategier förbereds Strategier. Vidare betonar resultaten behovet av djupgående förståelse för parametrar för att hålla helhetliga underhållsstrategier.
acronyms.tex

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```latex
%%% Local Variables :
%%% mode : latex
%%% TeX-master : t
%%% End :

% The following command is used with glossaries-extra
\setabbreviationstyle{long-short}
% The form of the entries in this file is \newacronym{label}{acronym}{phrase}
% or \newacronym[options]{label}{acronym}{phrase}
% see "User Manual for glossaries.sty" for the details about the options, one example is shown below
% note the specification of the long form plural in the line below

\newacronym{DB}{DB}{Deutsche Bahn AG, German Railway}
\newacronym{SBB}{SBB}{Schweizerische Bundesbahnen AG, Swiss Federal Railways}
\newacronym{EU}{EU}{European Union}
\newacronym{SNCF}{SNCF}{Société nationale des chemins de fer français, National society of French railways}
\newacronym{EMU}{EMU}{electric multiple unit}
\newacronym{UIC}{UIC}{Union internationale des chemins de fer, International Union of Railways}
\newacronym{CHE}{CHE}{Switzerland}
\newacronym{ITA}{ITA}{Italy}
\newacronym{WTT}{WTT}{working timetable}
\newacronym{FMS}{FMS}{fleet management system}
\newacronym{UFD}{UFD}{Unterflurdrehrbank, wheel turning machinery}
\newacronym{UMB}{UMB}{Ueberfahrmessanlage, drive-over measurement system}
\newacronym{ENIV}{ENIV}{Einheitswagen IV, single deck passenger coach}
\newacronym{IC2000}{IC 2000}{Intercity 2000, double deck passenger coach}
\newacronym{UUB}{UUB}{leading unpowered bogie, ELDC}
\newacronym{JUB}{JUB}{Jacobs unpowered bogie, JLDG}
\newacronym{JPB}{JPB}{Jacobs powered bogie, JMDG}
\newacronym{UB}{UB}{unpowered bogie, LGD}
\newacronym{PB}{PB}{powered bogie, TDG}
\newacronym{UNS}{UNS}{unpowered wheelset, LRS}
\newacronym{PWS}{PWS}{powered wheelset, TRS}
\newacronym{ICE}{ICE}{Intercity-Express}
\newacronym{HALL}{HALL}{hydraulisches Achslenkerlager, hydraulic wheelset guidance}
\newacronym{AC}{AC}{alternating current}
\newacronym{ERP}{ERP}{enterprise resource planning}
\newacronym{RDS}{RDS}{Rail Data Services}

% To get the .acr file filled run pdflatex (play button). Afterwards open console of "thesis" folder and type "makeglossaries thesis" + enter. Rerun pdf latex
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