Probabilistic review of wheel profiles based on hollow tread in the U.S. heavy haul rail network

Jaeik Lee, Marcus S Dersch, Arthur de Oliveira Lima and J Riley Edwards

Abstract
Wheel profile is one of the most critical factors that governs the dynamic interaction between railcar wheels and the rail. This paper quantifies and analyzes 15,000 wheel profiles that were randomly selected from a dataset obtained from wayside wheel profile measurement systems from railcars that are in unrestricted interchange in the North American Class I railroad network. Mean dimensions for each of the four critical wheel tread parameters were as follows; 30.5 mm (1.202 in.) for flange height, 35.4 mm (1.395 in.) for flange thickness, 0.483 mm (0.019 in.) for hollow tread, and 37.8 mm (1.488 in.) for rim thickness. Further evaluation focused on the magnitude of hollow tread, one of the important factors that determines wheel rail contact location, contact patch size, and dynamic interaction of the railcar and track. Correlative analysis revealed that hollow tread is linearly related to flange height, flange thickness, and rim thickness. Given this relationship, we categorized wheel profile data into characteristic bins of wheel profiles, and a new classification system based on hollow tread was proposed that should be considered when designing track infrastructure components (e.g., turnout frogs). Combinations of parameters were derived and organized into five wheel-profile classification ranges, based on “most likely” to “least likely” profiles that might be encountered. For the five classifications (Type A to Type E), a range of hollow tread from 0 mm to 5 mm (interval of 1 mm) and corresponding mean values for the three other parameters were applied. This probabilistic analysis and classification of wheel profiles into categories enables better understanding of current North American wheel conditions. Additionally, these data and the proposed analysis method can be leveraged to further optimize wheel profiles and track components, identify relationships with rates of rail surface defects and track degradation, and prioritize maintenance.

Keywords
Hollow tread, probabilistic review, railcar wheel, wheel classification, wheel profile

Introduction

Background
Maintaining proper wheel profile is essential given it governs the interaction between wheel and rail and closely relates to the dynamic performance of rail vehicles. Magel et al. identified that proper design and application of optimized profiles can double wheel life, mitigate noise and corrugation issues, considerably extend the rail grinding interval, lengthen the period of stable running, and dramatically reduce levels of plastic flow, rolling contact fatigue, and wear. Additionally, the lack of proper wheel profiles can pose safety concerns, some of which can lead to derailments. Based on a review of Federal Railroad Administration (FRA) accident data for all mainline and sidings freight train derailments from 2000 to 2019 (9672 records), 27% of derailments (2611 records) resulted from equipment-related causes. Among them, 54% (1409 out of 2611) of the equipment causes were related to wheel, axle, or bearing defects, and 25% (660 out of 2611) of causes were directly related to wheel failures.

Over the past several decades, advancements have been made in the design of both high-speed rail and heavy axle load freight rolling stock, and the topic of vehicle/track interaction and maintenance of the wheel-rail interface have seen increased attention. Shevtsov et al. attempted to optimize the wheel profile based on the wheel/rail rolling radius difference, which promotes steering in curves and has a significant influence on the dynamic vehicle performance. Lu et al. introduced non-linear numerical optimization of wheel tread profile using genetic algorithm (GA) method. Liu et al. presented a procedure for design of wheel profile based on rolling radii difference and evaluated wheel/rail wear and safety requirements on curves using software ADAMS/Rail. In another study, Cui et al.
introduced a new wheel profile design to mitigate lateral accelerations and safety concerns.\textsuperscript{9}

Much of the prior research documented in literature was conducted with the objective of reducing wheel-related service failures and derailments during train operation by introducing new wheel profiles. It is widely understood that wheel profiles affect the dynamic behavior of rolling stock.\textsuperscript{10,11} and suboptimal wheel or rail profiles can result in accelerated wear or damage to the rail and/or the wheel.\textsuperscript{12} To ensure safe train operations, modifications in wheel and rail profiles must be evaluated and understood from a systems level, as they may alter rail vehicle stability and increase derailment risk due to wheels climbing the rail.\textsuperscript{13}

As a part of this analysis and optimization process, a comprehensive review of the existing wheel profiles in the U.S. is needed. A representative compilation and classification of current wheel profiles provides value in understanding the rates of rail surface and track degradation and provides a baseline for future optimization of track component (e.g., turnout frog, rail profile, etc.) designs.

A review of literature provides insight into previous efforts to optimize track components based on revenue service wheel profiles. Pålsson et al. used the European S1002 wheel profile to optimize railroad switches and crossings.\textsuperscript{14} Wan et al. used the S1002 and High-performance Individual Trainprofile to optimize railway crossing geometry for new and worn profiles.\textsuperscript{15} Most examples of prior research into the optimization of various track components have applied the design wheel profile, without consideration of damage or wear associated with actual worn profiles. A smaller body of research applied actual wheel profile data. Pålsson et al. conducted a study to optimize the railroad crossing geometry by applying 120 field-measured wheel profiles.\textsuperscript{14} However, given the geometry of wheels and rails is complex, there is a need for additional data to properly represent revenue service conditions.

**Approach**

While the wheel profile is composed of several parameters (e.g., hollow tread, flange height, flange thickness, rim thickness, and etc.), hollow tread is often considered to be the most important. Hollow tread is one of the important factors that determines wheel-rail contact location, contact size, and dynamic interaction of the railcar and track.\textsuperscript{16} For these reasons, many studies have focused on hollow tread. Tavakkoli et al.\textsuperscript{17} investigated the effect of hollow-worn wheels on the dynamic behavior of a passenger coach and showed that hollow-worn wheels with a depth of greater than 2 mm induce lateral oscillations of the railcar and increased the risk of truck hunting. Sun et al.\textsuperscript{18} developed a non-uniform rail wear prediction model to analyze the influence of hollow-worn wheels on rail wear. The results show that a slightly worn wheel will not cause a notable change in the wear distribution and the wear rate; however, substantial hollow wear will cause a dramatic increase in the lateral width of the rail wear area and the wear rate. Sawley et al.\textsuperscript{19} surveyed the characteristics of the hollow-worn wheels in North America and then quantified the effect of the depth of hollow wear on the wheel-rail dynamic interaction based on simulation result using software NUCARSTM.

Given prior research has identified the importance and influence of hollow tread as a parameter, this paper focuses on quantifying and analyzing revenue service wheel profile data from the United States Class I railroad network (made up of railroads with annual gross revenues more than $504,803,294 USD in 2019) with a specific focus on hollow tread. The objective of the research is to document the composition of wheel profile parameters and to conduct a probabilistic distribution analysis to understand the magnitude of their deviations from the design profiles maintained by the Association of American Railroads (AAR).\textsuperscript{20} Also, based on a correlational relationship of hollow tread to the other three wheel-profile parameters, a new classification system for wheel profile based on hollow tread is proposed. As a case study, representative cases for each classification group were identified for further consideration and application and are proposed as one of the paper’s conclusions.

For the analysis described in this paper, 15,000 wheel profiles were randomly selected from a larger dataset containing two million profiles obtained from wayside laser-based wheel profile measurement systems (described in more detail in the ‘measurement equipment and method’ section). These systems are in revenue service operation on Class I railroads in the U.S. Creating representative classification system is difficult, given the number of variables that must be taken into consideration. Therefore, classification of wheel profiles in this paper were performed based on the approximate range of each parameter’s dimension. Execution of this study will generate representative wheel profiles and other data for track component designers and railway managers that are tasked with wheel and rail maintenance. The objective of this work is to quantify and understand the current distribution of wheel profiles in revenue service, and not the development of a new wheel profile design.

**Theoretical discussion**

**Wheel profile defects & parameter**

Wheel defects and failures directly affect train operation and occupy valuable track infrastructure capacity and human resources during both railcar inspections and maintenance activities. Therefore, to reduce the likelihood of service failures, it is crucial to proactively reduce the number of faulty wheels. Wheel defects can be classified into different failure categories based on their associated root causes and failure mechanism(s) (Figure 1).\textsuperscript{21} Wheel profile defects are the focus of this research.

The profile of a wheel is often described using a variety of discrete measurements that help to define its shape.\textsuperscript{22} The most common parameters include flange height, flange thickness, hollow tread, rim thickness (Figure 2(a)).\textsuperscript{22} Flange height is calculated as the difference between a point on the tread 70 mm from the back of the flange and the top of the flange in the radial direction. Flange width uses the width of the flange 10 mm above the same point on the tread.\textsuperscript{23} Hollow tread is calculated as the maximum and minimum values within the specified limits and a comprehensive comparison between new wheel and worn wheel (Figure 2(b)). Lastly, rim thickness is calculated as the vertical distance between the internal rim diameter and a
point on the wheel rolling circle located a preset distance away from the wheel face.

It is well known from heavy axle load (HAL) freight railroad operations that hollow tread wear is detrimental with respect to the initiation of rolling contact fatigue (RCF). Therefore, limiting the depth and controlling the shape of hollow tread is important when designing an optimal wheel profile. In the revenue service operating environment, the negative impact of hollow worn wheels manifests itself in terms of:

- Increased rolling resistance and thus fuel consumption.
- Increased rail wear.
- Increased wheel flange wear.
- False flange damage to the rail surface and special track work.
- Increased lateral forces in curved track.
- An increased risk of truck hunting or other unsound running behavior on tangent track.
- Potential for wheel-related derailments.

**Wheel profile limitation standards in U.S.**

The AAR establishes and maintains wheel profile parameters that define wheel wear limits and expected levels of maintenance. A wheel needs to be re-profiled (referred to as “trueing”) when some of the measures exceed a given threshold, or when some type of wheel failure occurs such as RCF. The intervals between wheel re-profiling vary greatly depending on the application in question. The life cycle of wheels of lighter railcars is typically longer and the interval between re-profiling can vary from 200,000 to 300,000 km (124,274 to 186,411 miles). The thresholds for each wheel profile parameter for North America are shown in Table 1, as defined by AAR.

**Various wheel profile review**

The following section introduces four common wheel profiles used in the U.S. (Figure 3). These include the American Public Transportation Association (APTA) 340, AAR-2A, AAR-1B, and Unipoint wheel profiles.

The APTA 340 profile was developed by Center for Surface Transportation Technology (CSTT) and exhibits a lower flange thickness wear rate and improved vehicle stability compared to the previous (Amtrak) profile. The AAR-1B profile is widely used for freight train wheels in the U.S. Some commuter railroads adopted the AAR-1B flange standard, because the profiled flange wears into a relatively optimal contour for maintaining a steep flange angle. The AAR-1B profile has a 37.5 mm (1.5 in.) radius between the tape line and the flange that matched the typical worn wheel and rail profiles of the time. The intention of the AAR-1B profile was to avoid the initial
“wearing-in” stage and reduce wear on the rails. In case of AAR-2A, the design was recently implemented for use in North American freight railway operations to provide improved service performance for wheelsets. The design is based on the analysis of 210 pairs of rail profiles and 122 wheelsets. The final version of the AAR-2A profile includes a reduction in flange thickness of 3.2 mm (1/8 in.) to address the accelerated flange wear experienced by a new AAR-1B profile, and to improve high speed stability and curving performance.

Lastly, the Unipoint wheel profile has a wide flange wheel profile with a 1:20 taper tread and was designed to provide single point contact with the rail, thereby improving flange wear life. The Unipoint wheel has a 4 mm (5/32 in.) wider flange which increases the rim width by 1.6 mm (1/16 in.). The Unipoint wheel is not recommended for speeds above 105 km/h (65 mph), as the higher effective taper of the Unipoint wheel profile reduces the speed at which hunting occurs.

Measurement equipment and method

Wheel profile measurement equipment

Wheel profile data used in this research were obtained from revenue service Wheel Profile Measurement Systems (WPMS). WPMS, also known as Wheel Profile Detectors (WPD), are wayside detectors that capture wheel profile measurements using a laser-based scanning system coupled with high-speed digital cameras. WPMS measure flange height, flange thickness, rim thickness, and hollow tread (Figure 2(a)). WPMS data are used to inspect wheels for preventative maintenance, maintenance scheduling, and derailment prevention purposes. They are also used to remove bad actors thus mitigating track and rail damage caused by excessively worn wheels. WPMS can collect data at speeds of up to 140 km/h (85 mph), and are operable in the temperature ranges from −40°C to 55°C. For the following analysis, wheel profile data were obtained from three different field sites using four WPMS which were provided by two different vendors.

Data analysis and results

Wheel profile distribution results

Based on a randomized sample of 15,000 wheel profile data, mean values and distributions were derived. Also, probability distribution functions (PDFs) and percent exceeding plots were developed for each parameter (Figure 4). For each parameter, the number of wheels exceeding the allowable AAR limits were analyzed (Figure 5).
Figure 4. Distribution of wheel profile for each parameter (a) Distribution depending on parameter dimension (b) Excessive accumulative probability.

Figure 5. Comparison of profile data to Association of American Railroads limits for each wheel profile parameter (a) Flange height (b) Flange thickness (c) Hollow tread (d) Rim thickness.

Figure 6. Correlation between hollow tread and three other wheel profile parameters (a) Flange height (b) Flange thickness (c) Rim thickness.
<table>
<thead>
<tr>
<th>Division</th>
<th>Type A (76.94%)</th>
<th>Type B (16.93%)</th>
<th>Type C (4.34%)</th>
<th>Type D (1.5%)</th>
<th>Type E (0.29%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Range</td>
<td>Mean</td>
<td>Range</td>
<td>Mean</td>
<td>Range</td>
</tr>
<tr>
<td>Hollow tread</td>
<td>in</td>
<td>0.000–0.039</td>
<td>0.008</td>
<td></td>
<td>0.039–0.079</td>
</tr>
<tr>
<td></td>
<td>mm</td>
<td>0.000–1.000</td>
<td>0.205</td>
<td></td>
<td>1.000–2.000</td>
</tr>
<tr>
<td>Flange thickness</td>
<td>in</td>
<td>0.962–1.727</td>
<td>1.409</td>
<td></td>
<td>0.935–1.788</td>
</tr>
<tr>
<td></td>
<td>mm</td>
<td>24.43–43.87</td>
<td>35.789</td>
<td></td>
<td>23.75–45.42</td>
</tr>
<tr>
<td>Rim thickness</td>
<td>in</td>
<td>0.755–2.654</td>
<td>1.478</td>
<td></td>
<td>0.751–1.957</td>
</tr>
</tbody>
</table>
Additionally, correlation between three other parameters with hollow tread were described, and wheels were classified into five categories (Type A to Type E). Categories were based on hollow tread dimensions from 0 mm to 5 mm (1 mm intervals), and corresponding values for the three other parameters to classify from Type A to Type E.

Additionally, the data were compared to current AAR limits for the purpose characterizing the health of current wheels, and the results are shown in the Figure 5 for each parameter.

For each wheel profile parameter, most of the measured wheel profile values were within the allowable AAR limit. The number of wheels beyond the AAR limit was 55 wheels (0.37%) for flange height, four wheels (0.03%) for flange thickness, 53 wheels (0.35%) for hollow tread, and 79 wheels (0.53%) for rim thickness. Additionally, a correlative analysis between hollow tread and the other three parameters was undertaken to formulate representative wheel profiles that can provide a basis for a new classification system of the wheels currently used in the U.S. Initial results from this categorization procedure (with mean values for each type) are shown in Figure 6.

Hollow tread has linear relationship with the other three wheel-profile parameters (flange height, flange thickness, rim thickness). It shows a linearly increasing relationship with flange height, and a linearly decreasing in relationship with both flange thickness and rim thickness. For classifying wheel profile, and when binning hollow tread from 0 to 5 mm (in 1 mm interval), the corresponding value of the other three wheel-profile parameters were used. From 0 to 1 mm of hollow tread and corresponding mean values of other three parameters were classified as Type A. The same method was applied to classify Type B to Type E, with the range and average value for each parameter according to classification type shown in Table 2.

Based on the chosen classifications (Type A to Type E), a radar chart was developed to visually compare of each type (Figure 7). Mean dimensions for the three critical parameters (flange height, flange thickness, and rim thickness) are described in Figure 7 for types A to E. As the classified wheel type changes from type A to E (i.e., increasing hollow tread) there is an increase of flange height (star shape) and decrease for both flange thickness (circle shape) and rim thickness (square shape). Also, by using the average value for each parameter, representative wheel profile shapes (from type A to E) and AAR-2A wheel profile (which recently implemented in North America) are presented in Figure 8.

Among the wheel profile classifications, Type A accounts for the largest portion (77%) of the actual wheel profiles which are in operation, and from Type B to Type E account for 17%, 4%, 1.5%, and 0.3% of the population.
respectively. The above five classifications bound typical wheel profile shapes (Type A) and outlier profiles (Type E). Therefore, the probabilistic review and classification of wheel profile enables a better understanding of current wheel profiles in the U.S. These classifications can be used as a baseline for track component design optimization or for establishing future wheel profile maintenance standards in the railroad industry.

Conclusions
This paper describes the approach and characterization used for a probabilistic review of railcar wheel profiles that were measured during revenue service operation on U.S. Class I railroads. From the analysis and classification of 15,000 randomly-sampled revenue service wheel profiles, the following conclusions are presented:

- The distribution for each wheel profile parameter was derived, and mean values for each parameter were found to be 30.5 mm (1.202 in.) for flange height, 35.4 mm (1.395 in.) for flange thickness, 0.483 mm (0.019 in.) for hollow tread, and 37.8 mm (1.488 in.) for rim thickness.
- Among randomly selected 15,000 wheels, the number of wheels that exceed AAR limits for wheel profile parameters were 55 wheels (0.37%) for flange height, four wheels (0.03%) for flange thickness, 53 wheels (0.35%) for hollow tread, and 79 wheels (0.53%) for rim thickness. This indicates that the vast majority of wheels sampled at the revenue service locations studied in this project were healthy wheels that are in compliance with industry standards.
- Correlation analysis between hollow tread and the other three parameters showed a linear relationship: increasing with flange height, and decreasing for flange thickness and rim thickness. Based on the relationship between these parameters, hollow tread dimensions from 0 mm to 5 mm (1 mm interval) and corresponding values for the three other parameters were classified into five types (e.g., wheel dimension of hollow tread range from 0 mm to 1 mm and corresponding mean values of other three parameters were classified to Type A, and same method was applied to other four types from Type B to Type E).

The above conclusions provide a method for improved characterization of current wheel profiles that can be utilized in establishing future wheel and rail maintenance standards. Furthermore, five types of wheel profile classifications which were made based on most likely (Type A) to least likely (Type E), could be utilized in the optimization of future track component design, which could mitigate the possibility of accidents caused by wheel profile deficiencies. Future wheel profile classification research should consider additional variables (e.g., cumulative tonnage, track condition, type of wheels, prevailing track geometry, etc.). As a result, more efficient classification may be possible providing even greater utility to designers of railway track components that interface with railcar wheels.

Author contributions
The authors confirm contribution to the paper as follows: study conception and design: J. Riley Edwards, Marcus Dersch, and Arthur Lima; data collection: J. Riley Edwards, Marcus Dersch, and Arthur Lima; analysis and interpretation of results: Jaeik Lee, J. Riley Edwards, Marcus Dersch, and Arthur Lima; draft manuscript preparation: Jaeik Lee, Marcus Dersch, J. Riley Edwards. All authors reviewed the results and approved the final version of the manuscript.

Declaration of Conflicting Interests
The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding
The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: This research was primarily supported through funding from the National University Rail Center (NURail).

Disclaimer
The positions presented within this paper represent those of the authors and not necessarily those of the US Department of Transportation.

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