Influence of Axle Load on the Wear of Railway Wheel Material

Hewan Getachew Yenealem,1 Daniel T. Redda,2 and Awel Mohammedseid1

1African Railways Center of Excellency, Addis Ababa Institute of Technology, Addis Ababa University, Ethiopia
2Associate Professor in Mechanical Design, School of Industrial and Mechanical Engineering, Addis Ababa Institute of Technology, Addis Ababa University, Ethiopia

Correspondence should be addressed to Hewan Getachew Yenealem; hewan.getachew@aait.edu.et

Received 19 October 2022; Revised 10 January 2023; Accepted 21 January 2023; Published 13 February 2023

This study investigated the influence of axle load on the wear rate of railway wheel material. Excessive wear of wheel/rail materials and reduced service life of the wheel/rail system might be caused by the increase in axle load and traffic volume. Two kinds of rail and wheel steels have been studied against different axle load steps, simulating them for wear performance analysis using multibody simulation software (SIMPACK) and MATLAB programming. The simulation model results are validated against the vehicle’s specifications and wear depth measured on Ethiopia—Addis Ababa Light Rail Transit (LRT), and experimental results from the literature. The result shows that the wear rate increases proportionally with the increasing of applied load and that the proportionality coefficient is 0.1393, which has a very good agreement with the experimental results from the works of literature. Likewise, the estimated total tread wear amount after a mileage of 52,000 km is 2% larger than the measured one in LRT, which is indeed an excellent result taking into account the inaccuracy of the wheel diameter gauge used to measure the wheel transversal profile. In normalized UIC 50 kg/m rail and S1002 wheel profiles, the wear rate increases linearly from 5110.02, 9997.87, and 18990.17 mm³/km on 11, 21, and 30 tones applied load, respectively. Apparently, on the hardened UIC 60 kg/m and S1002 wheel profiles, the wear rate has been improved by 14.5%, 10.8%, and 7.5% on 11, 21, and 30 tones applied load, respectively, in comparison to normalized rail/wheel match. Briefly, the wheel wear rate is highly influenced by the increasing applied load, referring proportionality coefficient of 0.1393.

1. Introduction

The wheel/rail interface plays a fundamental role in determining the reliability of railway transportation, especially for heavy-haul and high-speed railways. It is well known that the increase in axle load and traffic volume of railways leads to excessive wear of wheel/rail materials and remarkably decreases the service life of the wheel/rail system [1]. The wheel/rail contact area is typically the size of a small coin, and the material in and around the contact area is highly stressed. High wear rates might be expected for such a contact, and well-designed primary suspensions are essential to minimize the impact of these loads on track life and wheel life [2]. The maximum force applied by the wheel and rail mechanism depends on two parameters of the coefficient of friction at the contact surface and axial load [2]. A stagnation or slip phenomenon occurs when the wheel spins under the influence of torque to move the tube. Achieving the maximum coefficient of adhesion at high-speed insertion is usually done by using special materials in the contact area between the wheel and rail in addition to increasing the coefficient of friction.

Windarta et al. used a pin on the disc to determine the influence of load on wear rate and wear mechanism in rail steel materials [3]. The study used the same material for pin and disk testing under a rotating speed of 100 rpm. The equation determined the weight loss:

\[ m_{\text{pin}} = \rho_p \int_{A_p} u_n^d S. \]  (1)

Where \( m_{\text{pin}} \) is the mass of the pin, \( \rho_p \) is the mass density of the pin, \( A_p \) is the area of the contact, and \( u_n^d \) is the depth
Four kinds of rail steel were tested to investigate wheel–rail materials’ wear behaviors under three axle loads [4]. Rail disks are made of four kinds of rail steel: hot rolled U71Mn, quenched U71Mn, hot rolled U75V, and quenched U75V, whereas the wheel disks are made of CL60 wheel steel. Rolling–sliding wear tests are carried out to simulate a train passing through a straight line using an MMS-2A rolling–sliding testing apparatus. Results indicate that the increase in axle load not only significantly enlarges the wear loss but also the depth and length of the fatigue cracks. The relationship between the total wear loss of the wheel/rail system and the hardness ratio indicates that the hardness ratio of wheel/rail steel has a slight impact on the total wear loss at low axle load; however, the decrease in the hardness ratio enlarges the total wear loss significantly at a high axle load. The effect of increasing the axle load on the effective frictional coefficient available at the wheel–rail interfaces during high-speed railway operations was quantified by numerical simulations [5]. Numerical analyses were run simulating train operations at speeds of 160 km/h, which is the maximum operational speed of a train running in Indian Railways on date (the operational speed of Gatimaan Express running between Delhi and Agra). The simulations were performed with train axle loads in the range of 20–32.5 tones, analyzing the axle load’s influence on the effective frictional coefficient available at wheel–rail interfaces. The results reveal that the net frictional coefficient available at the wheel–rail contacts has a trend towards increasing with an increase in the applied axle load. A multiple linear regression analysis (MLRA) method was used to identify influential parameters on rail wear [6]. The study investigates the effects of traffic loads and track parameters, including track curvature, superelevation, and train speed, on vertical and lateral rail wear. According to the results of MLRA for vertical and lateral wear, traffic load has a statistically significant effect on the amount of vertical and lateral rail wear; however, track curvature, superelevation, and train speed do not.

Briefly, based on those previous researches, only the rail material wear has been detected [3, 4, 6]. Besides, the same material was used for the pin and disk testing [3]. Structural steel was considered as the constituent material for both wheelset and rails, with an ultimate tensile strength of 880 MPa, and the material was supposed to follow a bilinear isotropic hardening behavior, and variation of the effective frictional coefficient at the wheel–rail interface was plotted, concerning the variation in the applied axle loads instead of wear rate calculations [5]. In the present research, two kinds of rail steels and wheel steel with respect to their rail/wheel matches were tested to investigate the wear behavior of wheel materials under three kinds of axle loads. Normalized UIC 50 kg/m rail and S1002 wheel profiles and hardened UIC 60 kg/m and S1002 wheel profiles have been studied against different axle load steps, simulating them for wear performance analysis using multi-body simulation software (SIMPACK) and MATLAB programming. The proposed simulation methodology results are validated against the vehicle’s specifications, derailment of coefficient, and maximum lateral force and compared to experimental results from literature. In advance, the wear depths measured on the wheel tread wear of the end vehicle of Ethiopia—Addis Ababa Light Rail Transit (LRT) for 11 tons of axle load and mileage of 52,000 km are compared to the results of the numerical simulation performed. The final results of this study are validated against the experimental results from the literature.

2. Materials and Methods

2.1. Methodology. From a mathematical point of view, the wheel–rail contact problem can be solved using the following four steps [7]. The first step is to solve the geometrical problem, followed by the normal contact problem, in which the shape and size of the contact patch are formed in the contact interface due to body deformation. The third step is to deal with the kinematic problem, in which normalized
kinematic quantities, the so-called creepages, are determined. Finally, the tangential problem is solved; this concerns the prediction of tangential stresses at the contact interface. The main objective is to investigate and determine the axle load’s influence on wear rate and wear mechanism of wheel materials in relation to hardness. Figure 2 shows the wheel wear prediction methodology.

From SIMPACK, we find the creep force and creepages in order to calculate the $T_{pama}$ and the contact patch. Next, the outputs from the vehicle–track simulations, which are normal forces, size of the contact ellipse semiaxis, contact patch location (lateral coordinate of center), and creepage (including spin), form the input to the wear model. The wear model, developed separately in MATLAB, relates the quantities in the contact surface to the wear depth on the profile, and then a wear distribution is calculated. Wear depth is estimated to create a worn wheel profile. Lastly, the wear distribution and the new wheel profile are smoothed in every wear step using a cubic spline interpolation algorithm. Then, the updated (worn) profile serves as the initial profile in the following wear step. This way, both rail/wheel materials match are simulated with different axle loads until the desired running distance is attained. To avoid the possibility of the predicted wheel profile deviating into unrealistic shapes, the maximum allowed wear depth perpendicular to the profile is set to 0.1 mm [8]. Wear effect and mechanism of axle load for the softer and harder rail/wheel matching materials will be verified against field measurements and experimental results; and the effect of axle load and material hardness concerning on-wheel wear has been determined.

**2.2. Application.** The present wear prediction tool is applied to a vehicle operating the commuter rail network in Ethiopia—Addis Ababa LRT. In light rail, the vehicles provide transportation service in two main lines: the east–west line and the other north–south line. The total length of the line is 31.025 km, where the east–west main line is around 16.99 km long and the north–south main line is around 16.689 km long [9]. The two lines share a 2.662 km section. Table 1 shows the general technical parameters and condition of freight car of the National Railway of Ethiopia [Source: Ethiopian Railway Corporation, technical specification of vehicle].

<table>
<thead>
<tr>
<th>Technical values</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Railway gauge</td>
<td>1435 mm</td>
</tr>
<tr>
<td>Loading capacity</td>
<td>70 kg</td>
</tr>
<tr>
<td>Wheel diameter</td>
<td>600 mm</td>
</tr>
<tr>
<td>Maximum speed</td>
<td>80 km/h</td>
</tr>
<tr>
<td>Axle load</td>
<td>$\leq 11 (1 + 3%)$ tones</td>
</tr>
<tr>
<td>Minimum radius of vertical curve</td>
<td>1000 m</td>
</tr>
<tr>
<td>Maximum gradient</td>
<td>55%</td>
</tr>
<tr>
<td>Empty vehicle load</td>
<td>44 tone</td>
</tr>
<tr>
<td>Type of rails for main lines and depot</td>
<td>50 kg/m</td>
</tr>
</tbody>
</table>

Source: Ethiopian Railway Corporation, technical specification of vehicle.

**Figure 2:** Wheels wear prediction methodology.

Table 1: Technical parameters of passenger car for Addis Ababa light railway transit.
wheel materials are tested with different axle loads (11, 21, and 30 tons) with the same speed, running distance, and other operating parameters.

2.3. Measurements of Wheel Wear. In Ethiopia, LRT vehicles are maintained at depots on a daily, annual, quarterly, and monthly basis. At wheel re-profiling workshops, underfloor wheel lathes are used to re-profile wheels (Figure 3(a)). The wears of wheels on the Addis Ababa LRT line were measured using a dial type wheel diameter gauge (Figure 3(b)). Measurements are made directly on the rolling stock without wheelset roll-out. The measurement of the diameter is performed according to the ‘three points’ technique, without the complete wheel coverage. Dial type wheel diameter gauge is a highly accurate railway wheel diameter measuring device, having accuracy of better than 0.05 mm. The gauge contains a numeric display to show the wheel diameter value and contains Bluetooth interface for transferring results into the wheelset wear database management system (Figure 3(c)).

The Ayat wheel re-profiling workshop conducted wear measurements from March 2017 to January 2017. Before the machining, the wheel treads were measured using a device. After the machining, the wheel treads were again measured using the same device. The results of the measurements are shown in Table 3. Five vehicles with an average running mileage of 52,000 km were inspected at Ayat depot. Table 3 shows the summary of vehicles that were inspected at Ayat depot with tread diameters.

3. Wear Prediction Model

Three-dimensional multibody models and a wear model have been used to predict wear for railway wheels running on a tangent line. The dynamics simulations of the vehicle—track interaction provide the forces that the wheel and rail profiles could experience. The wear model calculates the amount of wear on the wheel profiles using the output from vehicle—track interaction simulations (force, creepage, semiaxes of the contact ellipse) as an input. Wear depth is calculated to create a worn wheel profile. Then, the wear distribution and the new wheel profile are smoothed in every wear step using a cubic spline interpolation algorithm. The smoothing process is an essential point of the profile wear

Table 2: Chemical composition of candidate rail and wheel materials.

<table>
<thead>
<tr>
<th>Predicted wheel and rail materials</th>
<th>Chemical composition %</th>
<th>Hardness (BHN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normalized UIC 50/S1002 Wheel</td>
<td>0.4 0.35 0.8 ≤0.05 ≤0.05</td>
<td>200</td>
</tr>
<tr>
<td>Normalized UIC 50/S1002 Rail</td>
<td>0.6 0.3 0.8 ≤0.05 ≤0.05</td>
<td>240</td>
</tr>
<tr>
<td>Hardened UIC 60/S1002 Wheel Rim heat treated (hard) UIC S1002</td>
<td>0.6 0.1 1.3 ≤0.04 ≤0.04</td>
<td>260</td>
</tr>
<tr>
<td>Hardened UIC 60/S1002 Rail Whole heat treated (very hard) UIC 60</td>
<td>0.8 0.1 0.8 ≤0.025 ≤0.03</td>
<td>350</td>
</tr>
</tbody>
</table>

Table 3: Addis Ababa light rail transit (LRT)—Ayat depot vehicles inspected between March 2017 and January 2017 vehicle.

<table>
<thead>
<tr>
<th>Vehicle no.</th>
<th>Tread diameter (Td) in mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>111</td>
<td>659.3</td>
</tr>
<tr>
<td>108</td>
<td>659.7</td>
</tr>
<tr>
<td>114</td>
<td>659.8</td>
</tr>
<tr>
<td>110</td>
<td>659.2</td>
</tr>
<tr>
<td>115</td>
<td>659.8</td>
</tr>
<tr>
<td>Average Td/wheel</td>
<td>659.6</td>
</tr>
</tbody>
</table>
prediction model. Because they are changed after running some mileage, the wheel profiles should be updated, and a new calculation of contact force, traction, and slip should be performed. As too frequent profile updates could result in unnecessary computational effort, increasing mileage between two calculations may lead to inaccuracies in the final worn wheel profile or even divergence in the numerical procedure due to the non-updated wheel profiles in the multibody code. A sensitivity analysis showed that a threshold of 0.1 mm is very suitable to guarantee good accuracy and, simultaneously, does not lead to excessive computational effort [8]. The worn wheel profile must be then smoothed to avoid short wavelength concavities along the wheel profiles that are a combination of a moving average applied to the cumulative wear depth before profile update and a cubic smoothing spline used to the updated profiles before starting a new iteration of the wear model.

3.1. Vehicle–Track Interaction. The vehicle model of the 80 km/h Ethiopia—Addis Ababa LRT train is developed in the software SIMPACK and consists of a whole dynamic rigid multibody model with a car body, two bogie bolsters, two bogie frames, two traction link masses, four wheelset, and eight axle box connected by linear and non-linear suspension elements (90 degrees of freedom), Figure 4(a). The connecting elements between bodies are modelled realistically and reliably. The bogies are modelled, including all aspects of the system (Figure 4(b)). The SIMPACK model has been done to reproduce the functional characteristics of each suspension level in the best way. The inputs of the multibody code are the vehicle parameters and speed, the wheel and rail profiles, the track flexibility, the ideal geometry of the line, and wheel and rail irregularities. Wheel and rail profiles are described by discrete points, making it possible to update the profile by the procedure adopted to compute wheel–rail contact forces. This considers that contact between a single wheel and rail may occur simultaneously at more than one location. Figure 4 illustrates the MBS vehicle–track numerical model that was validated using field experiments.

3.2. Wheel–Rail Contact Modelling. The wheel/rail contact area is typically the size of a small coin, and, commonly, eight such contacts (i.e., eight wheels) support a vehicle weighing from 30 t (lightweight passenger coach) to 140 t and more (heavy freight). The material in and around the contact area is therefore highly stressed. High wear rates might be expected for such contact, but, in addition, the load is applied and removed many times during the passage of each train [1]. Different numerical approaches exist to estimate the normal force for a given contact patch. An ellipse is fitted in the contact area, and the normal force is calculated using the Hertz theory, known as the equivalent ellipse method. The computational effort using this method is very low, which is essential in railway simulation. The tangential problem is solved by the High-Speed Simulator (FASTSIM) algorithm based on the simplified theory developed by Kalker and has been widely used in railroad vehicle computer programs [10]. FASTSIM can calculate the pressure distribution and creep forces in the contact area, based on the information provided about the normal contact problem [11]. Creep is the ratio of sliding velocity (v) and vehicle speed (V). It can be broken down into three components: longitudinal creep, lateral creep, and spin creep [12].

\[
\text{Longitudinal creep: } \xi_x = \frac{v_x}{V},
\]

\[
\text{Lateral creep: } \xi_y = \frac{v_y}{V},
\]

\[
\text{Spin creep: } \varphi = \frac{\omega}{V},
\]

where \(\xi_x, \xi_y,\) and \(\varphi\) longitudinal, lateral, and spin creepages, respectively.

Creep forces are non-linear function of creepage and spin in the contact area with a maximum value of \(\mu N;\) however, the problem can be regarded as linear when the creep-age is assumed to be small [11].

3.3. Wear Model. The Archard wear equation is based on the theory of asperity contact, which was developed much later than the dissipative energy hypothesis. Both scientists arrived at the same conclusion that the amount of debris removed due to friction is proportional to the work done by the forces. In the present study, Archard’s law [8, 10–12] and FASTSIM are used to calculate the amount of wear. Archard’s wear model suggests that the volume of
material worn away is proportional to the sliding distance times the normal force and inversely proportional to the hardness of the worn material [13].

\[ V_{\text{wear}} = k_i \cdot \frac{s \cdot N}{H}, \]  

(5)

where \( k_i \) is the wear coefficient \([-\)], \( s \) is the sliding distance \([\text{m}]\), \( N \) is the normal force \([\text{N}]\), and \( H \) is the hardness of the material \([\text{N/m}^2]\). \( k_i \) can be described as [12],

\[ k_i = \frac{(W/p) \cdot H}{F}. \]  

(6)

The wear coefficient \( k_i \) wear map (Figure 5) can be determined with the sliding velocity on the horizontal axis and contact pressure on the vertical axis. According to Archard, since the sliding distance is zero (zero sliding velocity), there is no wear on the sticking area of the contacts [8, 12]. The wear depth for each cell element (\( \Delta z \) \([\text{m}]\)) could be calculated:

\[ \Delta z = k_i \cdot \frac{p_z \cdot \Delta s}{H}, \]  

(7)

where \( p_z \) is the contact pressure in \([\text{N/m}^2]\). The wear depth, \( \Delta z \), is assumed that the initial wear acts in the direction normal to the undeformed wheel and rail profile. The sliding distance \( \Delta s \) can be treated as the distance that a wheel particle slides through the concerned cell element.

4. Analysis and Prediction of Simulation Results

The wear analysis is completed with the superposition between nominal and worn wheel profiles for two rail/wheel material matches; the current Ethiopia—Addis Ababa LRT rail/wheel matching (normalized UIC 50 kg/m rail and S1002 wheel profile) and rim heat treated S1002 wheel and whole heat treated UIC 60 rail (hardened UIC 60 kg/m and S1002 wheel profile), to evaluate the effect of axle load on the wear rate and mechanism of wheel material concerning material hardness.

4.1. Model Validation. The modelled Ethiopian—Addis Ababa LRT vehicle is simulated on a straight track with a running speed of 70 km/h. For validation of the wear prediction model of this study, before we proceed to the main scenario modelling and simulation, the results are validated against the vehicle’s specifications, derailment of coefficient, and maximum lateral force. From Figure 6(a), it can be observed that the derailment of the coefficient satisfies the standard \((Y/Q < 0.8)\). Accordingly, in Figure 6(b), the lateral force also fulfils the standard \( Y < 60 \text{ kN} \) according to UIC 518, 2005.

4.2. Comparison with Field Measurements. In Figures 7(a) and 7(b), the wear depths measured on the wheel tread wear of the end vehicle of Ethiopia—Addis Ababa LRT for 11 tons of axle loads and mileage of 52,098 km are compared to the results of the numerical simulation performed. The trailing unit of trains operating in the east–west line (2XX) is chosen since the driven axles and tread brakes on the power unit would complicate the tool further. The trailing unit is only equipped with disc brakes, and it is justified to assume that all wear is due to rolling contact only. The computational results show that the numerical simulations performed using the wheel profile wear prediction model agree very well with the measurements. To be sure, the estimated total tread wear amount after a mileage of 52,000 km is 2% larger than the experimental one, which is indeed a very good result considering that either component of the wheel wear prediction model is neither an adjustment nor calibration. Furthermore, the inaccuracy of the wheel diameter gauge used to measure the wheel transversal profile should be considered.

4.3. Axle Load and Hardness Effect on Wheel Wear. This paper investigates the wear of wheel material with respect to axle load and material hardness effect. Figure 8 illustrates the influence of load on the wear depth of wheel material for both rail/wheel machining materials \((a, b)\). To overlook the influence of load on the wear of the wheel, a matching of normalized UIC 50 kg/m rail and S1002 wheel profiles and hardened UIC 60 kg/m and S1002 wheel profiles of a low-speed train running on Addis Ababa LRT has been simulated for a mileage of 50,000 km. During the wear tests, the normal forces are applied for both specific rail/wheel machining vehicle simulations. The axle loads of 11, 21, and 30 tons are selected. The wear rate calculation was done in dry conditions under a vehicle speed of 80 km/h. In the first rail/wheel machining, the current Ethiopia—Addis Ababa LRT rail/wheel machining, the rail and wheel hardness are 240 BHN and 200 BHN, respectively (normalized UIC 50 kg/m rail and S1002 wheel profile). In this scenario, the maximum wear depth increased linearly from 1.85, 2.78, and 4.01 mm with 11, 21, and 30 tons applied loads (Figure 8(a)), respectively. From the analyses, the wear depth on the wheel material increases 0.115 in proportionally with
the increasing of applied load. On hardened UIC 60/S1002, where the rail and wheel hardness were 350 BHN and 260 BHN, respectively (Figure 8(b)), the wear depth increased linearly from 1.58, 2.48, and 3.71 mm on 11, 21, and 30 tons applied load, respectively as well; which shows that the wear depth of wheel has been improved in hardened UIC 60 kg/m and S1002 wheel profile material comparing to the normalized UIC 50/S1002 on 11, 21, and 30 tons. Above and beyond, the wheel wear depth on the wheel material increases 0.113 in proportionally with the increasing of applied load, which shows the influence of applied load with valid conformation. Accordingly, the wear performances of various wheel/rail steels varied significantly depending on the increase in axle loads as well as the hardness of the steels used in the wheels and rails.

Figure 9 shows the wear rate of the wheel for both rail/wheel material matches with applied loads. In normalized UIC 50 kg/m rail and S1002 wheel profile, the wear rate increases linearly from 5110.02, 9997.87, and 18990.17 mm³/km on 11, 21, and 30 tons applied load, respectively. In the same way, for hardened UIC 60/S1002, the wear rate increases linearly from 4367.54, 8917.68, and 17570.12 mm³/km on 11, 21, and 30 tons applied load, respectively. This result shows that the wear rate increases with the increasing of applied load, and that the proportionality coefficient is 0.1393, which is an excellent agreement with Windarta et al. [3] experimental results. Apparently, in hardened UIC 60/S1002, the wear rate has been improved by 14.5%, 10.8%, and 7.5% on 11, 21, and 30 tons applied load, respectively, in comparison to normalized UIC 50 kg/m rail and S1002 wheel profile.
Use of ever-higher axle loads is mandated by the need for efficiency. Within the wheel/rail contact patch, which is typically the size of a small coin, and eight of these contacts—eight wheels—support a vehicle that weighs between 30 t (a lightweight passenger coach) and 140 t and more (heavy freight), a force exists normal to the plane of the contact, mainly due to the load of the wheel on the rail [1]. Since the material in and around the contact area is therefore highly stressed, high rates of wear might be expected for such a contact. Those analytical results are indications for the influence of applied load increment on the wear of railway wheel. The result shows that the wheel wear rate increases 0.1393 in proportionally with the increasing of applied load.

5. Summary

This study investigated the effect of axle load on the wear rate of wheel material on two rail/wheel matching materials running on Ethiopia—Addis Ababa LRT. Based on the aforementioned analysis, it can be said that different wheel/rail steels’ wear performances vary greatly depending on the rise in axle loads as well as the hardness of the steels used in the wheels and rails. Normalized UIC 50 kg/m rail and S1002 wheel profiles and hardened UIC 60 kg/m and S1002 wheel profiles have been studied against different axle load steps, simulating them for wear performance analysis using multibody simulation software (SIMPACK) and MATLAB programming. For validation, the wear prediction model of this study, before we proceeded to the primary scenario modelling and simulation, the results are validated against the specifications of the vehicle, derailment of coefficients, and maximum lateral force; and the result of both derailment of coefficients and lateral force satisfies the standard. Furthermore, the wear depths measured on the wheel tread of the end vehicle of Ethiopia—Addis Ababa LRT for 11 tons of axle load are compared to the results of numerical simulation. As so, the estimated total tread wear amount after a mileage of 52,000 km is 2% larger than the experimental one, which is indeed a very good result considering that neither component of the wheel wear prediction model used is adjustment nor calibration. In normalized UIC 50 kg/m rail and S1002 wheel profile, the wear rate increases linearly from 5110.02, 9997.87, and 18990.17 mm³/km on 11, 21, and 30 tons applied loads, respectively. Apparently, on the hardened UIC 60 kg/m rail and S1002 wheel profile, where the rail and wheel hardness are 350 BHN and 260 BHN, respectively, the wear rate has been improved by 14.5%, 10.8%, and 7.5% on 11, 21, and 30 tons applied load, respectively, in comparison to normalized UIC 50 kg/m rail and S1002 wheel profile. This result shows that the wear rate increases proportionally with increasing applied load and that the proportionality coefficient is 0.1393, which has an excellent agreement with the experimental results.

6. Conclusion

In this research, two kinds of rail and wheel steels concerning their rail/wheel matches were tested to investigate the
wear behavior of wheel materials under three types of axle loads. The wear characterizations of normalized UIC 50/ S1002 and hardened UIC 60/S1002 material matches for a mileage of 50,000 km under different axle loads were performed. Based on the results, the following main conclusions have been made.

(i) Based on the aforementioned analysis, it can be said that different wheel/rail steels’ wear performances vary greatly depending on the rise in axle loads as well as the hardness of the steels used in the wheels and rails. The wear rate increases linearly from 5110.02, 9997.87, and 18990.17 mm³/km on 11, 21, and 30 tons applied load, respectively, for normalized UIC 50 kg/m rail and S1002 wheel profile. The simulation result shows that the wear rate increases 0.1393 proportionally with increasing axle load, which agrees well with Windarta et al. [3] experimental results.

(ii) On hardened UIC 60 kg/m and S1002 wheel profile, the wear rate has been improved by 14.5%, 10.8%, and 7.5% on 11, 21, and 30 tons applied load, respectively, compared to normalized UIC 50 kg/m rail and S1002 wheel profile. This result shows that within the experimentally accepted range, the improvement of rail and wheel material positively affects the wheel rate.

(iii) Briefly, the wheel wear rate is highly influenced with the increasing of applied load, referring proportionality coefficient 0.1393.

Data Availability
The data used to support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest
The authors declare that they have no competing interests.

Acknowledgments
The authors wish to extend their thanks to African Railways Center of Excellency (ARCE) for supporting this research. This research is funded by World Bank Group.

References