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A Study of the Wear Behavior of a Rail Material

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A B S T R A C T

The rail track is one of the most important elements of a railway system. During the passage of trains, the rails are subjected to contact load that comes from the wheels of the train. The railway track often fails in service due to wear caused by contact fatigue and other wear damage mechanisms that could also limit the life span of the railway infrastructure and railway vehicle. The aim of this research is to investigate the wear behavior of a railing material under the effects of variable vehicle loads, coefficient of friction, and running speed of the train. In this study, wear parameters (wear rate and wear volume) are analyzed by numerical modeling using SIMPACK. The wear behavior of Addis Ababa light rail transit rails was studied (on the straight track section of the north-south line) by considering variables: wheel load conditions of empty, full capacity, and overloading train; dry contact boundary friction condition (0.1 to 0.5 coefficient of friction); and typical light trail running speeds (0 to 70 Km/hr.). The increase of applied load, coefficient of friction, and running speed results in an increment of wear rate and wear volume of the track surface. From the study, it was found that the highest specific wear rate for the overload capacity of the train (fixed coefficient of frictions and speeds) is 1.271234 x 10-4 mm 3/Nm, while the lowest specific wear rate is 0.000453 x 10-4 mm 3/Nm. The highest specific wear rate occurred at the maximum operating speed of 70 Km/hr. T (fixed loading conditions and coefficient of frictions), while the lowest specific wear rate occurred at a speed of 20 Km/h. This shows that to increase the wear life of the rails in Addis Ababa light rail transit. It is imperative to use optimal loading conditions, a lower coefficient of friction (0.25 to 0.35), and a medium running speed. (20 to 40 Km/hr.).

1. Introduction

Since the first iron track was developed in 1738 [1], railways have been playing an important role in public transportation. In Ethiopia, The first rail transportation (train service) began on July 22, 1901 [2]. Again, in September 2015, Ethiopia introduced the first light rail transits system at Addis Ababa city (ALART)[3]. It was the first in Sub Saharan Africa which joined the few African capitals with urban train facilities. The $475 Million worth environmental friendly light railway transport started service on September 20, 2015 charging the lowest fare of 2 Birr per 4km [4]–[6].

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Thus, the present study focuses on Addis Ababa light rail transit real conditions and specifications.

The railway transport system is one of the most crucial transport systems in the world with mass transport, very high speed, safety, and durability. Nowadays, there is a high demand for railway transportation systems in the world, including in Ethiopia, for short and long-distance transport of passengers and goods. The new rail network in Ethiopia and the railway track must show the necessity of efficient management of railway systems. The design must aim toward reducing costs and increasing safety, as well as reliability of the railway systems. The wheel/rail interface is one of the most crucial points that must be checked to determine the performance of a train and consider its safety [7].

Railway transport during the last years has increased in speed, security, and comfort. In comparison to automobiles, railway transport is a more secure and less environmentally damaging means of transportation. In order to keep up the competitiveness of railroad transportation, increasing requirements on the speed of passenger and freight trains, on the axle load of the trains, as well as the comfort of the passengers, have to be met. Further pressure on the development arises from the demand of decreasing the costs of both new trains and new rail tracks as well as the maintenance costs. Thus a large number of investigations have focused on the optimization of trains, rail tracks, and the rail/wheel system. For instance, optimizing the rail top profile. The mechanisms of material changes at the rail-wheel interface also have received considerable attention. But, so far, the structural changes that occur in the rail and the wheel material during service still have not been completely solved and clarified. In service, the surface of the rail track, as well as the surface of the wheel sets, are subject to great changes due to their long time sustaining load and wear. The damages that affect the mechanisms of wear are some of the concerns for the life prediction for railway rails. Wear causes abrupt fractures in the railhead and wheel tread. These failures may cause damage to rails because of the stress caused by the contact force. This study presents the experimental investigation of wear damage due to cyclic axle load on the rail and wears life for the light rail transit (LRT) in Addis Ababa, Ethiopia.

Some of the recent research in the field of wheel/rail tribology includes but is not limited to; contact mechanics involving forces and relative motion between the wheel-rail rolling contact, rolling contact fatigue in crack formation, and crack growth in the material close to, or at the wheel-rail interface, fracture mechanics which deals with the strength of cracked components and can be employed to predict final fracture of a rail, research on materials which concerns both the refinement of existing materials and the development of new types of materials, study on tribology is necessary to understanding and optimizing the wheel-rail interface and research on the railway which noise includes its generation, radiation, and propagation to the surroundings and to the passengers' cabin.

One of the importance of studying rail wear is to improve the safety of the railway infrastructure. Some authors [8], [9] has done work regarding safety of railway infrastructure. While other researchers [10], [11], [20]–[22], [12]–[19] have studied on the wear of railway rails. Dirks [15] opined that the location of the highest wear on rails depends on whether the rail is located in a curve or on straight track. Two examples of what worn rails can look like is shown in Fig. 1. In a curve, the rail is exposed to higher creep forces and creepages and will show more wear. Since the wheel-rail contact on the outer (high) rail in a curve is located at the gauge corner, the highest wear will take place here as well.

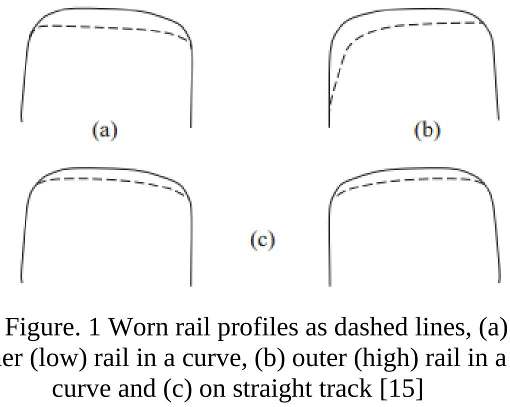

Figure. 1 Worn rail profiles as dashed lines, (a) inner (low) rail in a curve, (b) outer (high) rail in a curve and (c) on straight track [15]

Majority of the wear on the railway rail is caused by the impact of the wheel load on the railway track. Railway rails are subjected to a range of loading conditions, from light to heavy rail vehicles and low to very high velocities as well as arctic to tropic environments [23]. The maintenance costs of rails and wheels are mainly influenced by wear and rolling contact fatigue (RCF) [15]. The two most important component of railway rail damage are damage caused by rolling contact fatigue and damage caused by wear mechanisms. It is worthy to note that, as wear of the rail increases, the fatigue life of the rail also reduces. The wear of materials has been characterized by weight loss and wear rate. However, Studies have found that wear coefficient is a more suitable factor [24].

Safety is a major public concern in our daily life. Annually, people have lost their lives due to railroad accident which is caused by faulty railway tracks. Electric railway is new in Ethiopia and as railway transportation continues to be an important piece to the overall national transportation puzzle in Ethiopia and as congestion continue to increase on the nation's roadways, commuters continue to flock to public transit as an alternative transportation mode. Processes such as wear, friction and vibration can cause significant damage to the rail and wheels. Wear reduces the lifespan of the railway rails and increases maintenance cost and hence increases the operational cost of the railway infrastructure. The wear behavior of rails in Ethiopia has not been studied extensively, we only have the information has provided by the railway company. Thus, this study intends to investigate the wear behavior of rails in AALRT by varying the vehicle load, coefficient of friction and speed in other to understand and predict the wear behavior of the rails.

The main objective of this study is to investigate the wear behavior of a railway track. The specific objectives is the numerical Modelling of the AALRT railway rail using multibody vehicle simulation and analyzing the effects of coefficient of friction, wheel load and operating speed on specific wear rate of the railway rail. This study is based on AA LRT real conditions and specifications.

2. Materials and Method

Addis Ababa light rail transit consist of East-west and South-north lines in Addis Ababa (Phase I) with total length of main lines around 31.025km, where the East-west main line is around 16.998km long; the South-north main line is around 16.689km long. Both lines share the same section of around 2.662km in the urban areas. Vehicles are 70% low floor modern trams with maximum operating speed of 70km/h and average travelling speed of 20km/h (average dwelling time of 30 seconds at each station). The line uses a track gauge of 1435mm and a standard rail type of 50kg/m with axle load of ≤11（1+3%）t. Fig. 2 shows the map of the Addis Ababa light rail transit map for both north-south line and east-west line.

2.1. Materials used for the study

In this study, the materials used for track and wheel are railway steels. The specific data related to composition and properties materials, geometric and dimensional characteristics of wheel-track interaction, and vehicle specifications are taken from Ethiopian Railway Corporation data sheet [25] . The chemical composition and the mechanical properties of the railway steel are reported using table 1 and table 2, respectively.

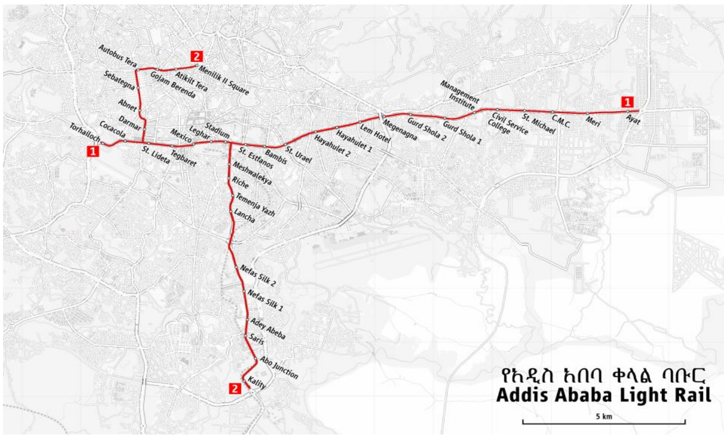

Figure. 2 Addis Ababa Light rail Transit Map

Table 1. Chemical compositions of the rail material

Rail material	C	Si	Mn	P	S	Ni	Cr
(%)	0.8	0.28	1.00	0.04	0.05	0	0

Table 2. Mechanical properties of the rail material

Mechanical property	Magnitude
Young's modulus	207GPa
Density	7800kg/m^3
Ultimate tensile strength	880 MPa
Yield strength	640MPa
Poisson's ratio	0.3
Elongation	>10%

The rail type used is UIC 60 rail. The rail is designed as a beam with the cross section of a UIC 60kg/m standard rail as shown in Fig. 3 and Fig. 4 shows the geometry of the rail and wheel profile.

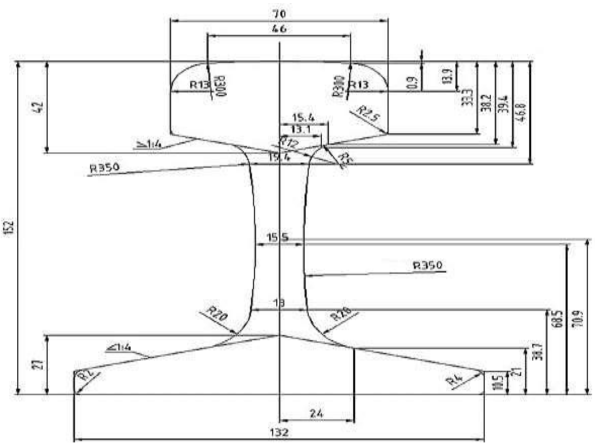

Figure. 3 Cross section of Addis Ababa light rail

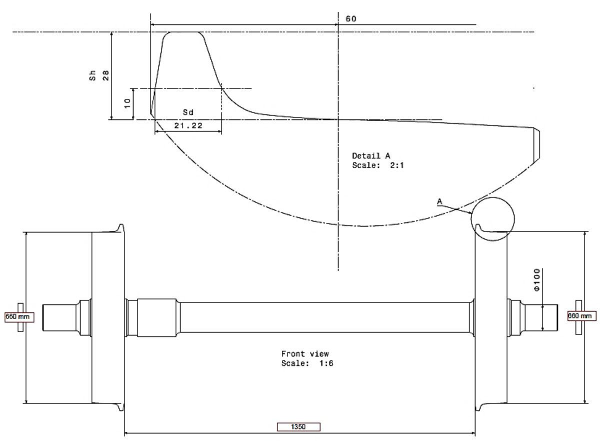

Figure. 4 Wheel Dimension for AALRT Vehicles

The maximum operating speed for each vehicle in AALRT is 70 km/h and the average travelling speed if 20km/h. the Table 3 shows the angular velocity in each case and vehicle specifications.

Table 3. Vehicle specifications and angular velocity.

Operating speed	Linear velocity(m/s)	Angular velocity (rad/s)	RPM
Maximum speed	19.44	58.92	562.65
Average speed	5.56	16.84	160.81

2.2. Numerical Analysis

Wear behavior is analyzed using numerical approach with help of SIMACK software. First, the vehicle-track interaction is modeled, and then wear parameters are determined at a variable loading conditions, coefficient of friction and running speeds.

2.2.1 Modelling of the rail vehicle on rail

The input parameters for modelling is given in Table 1 to 3. The model of the wheel on rail is given in Fig. 5.

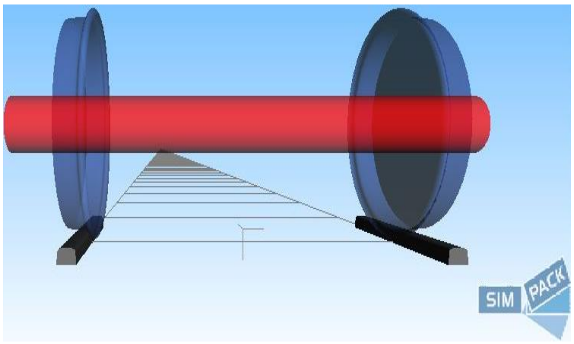

Figure. 5 Wheel on Rail contact model

In other to solve the model, the simulation is done for about 20 seconds.

Assumptions during simulation

- Track irregularity is not included so regular standard track is considered
- Wheel profile of the wheels are considered identical
- Simulation is done for different values of coefficient of friction (0.1, 0.2, 0.3, 0.4, 0.5)
- Simulations is done for three different capacity of the train capacity (empty, seating and overload capacity of the train).
- Simulation is done for different range of speed of the train (20 Km/h to 70 Km/h)

✓ Simulation is done only for the straight track section of AALRT, the curve portion is not considered.

The rail is designed as a beam with the cross section of a UIC 60kg/m standard rail as shown in Fig. 3. Wear is the gradual damage between materials involved in relative motion. For an unlubricated sliding condition such as the wheel or rail, the wear rate depends on the normal load, relative sliding speed, initial temperature and the thermal, mechanical and chemical properties of the material in contact [26]. Some of the factors that affect wear of rails are wheel load, speed, adhesion, material type etc. but for the purpose of this analysis, we shall be considering the effects of speed, coefficient of friction and wheel load on the wear of the rail material.

2.2.2. Hertzian Contact Patch formulation

In order to study the contact between bodies, first, contact parameters, such as contact surface area, the pressure and the tangential forces need to be determined based on the Hertzian contact theory for elliptical type contact elements (wheel track interaction is one example) [27].

If we consider the wheel and rail to be an elastic material in contact, they will meet at a single point O, where the normal distance between them is zero. Near this contact point, without load, the body surface shapes may be represented by two second-order polynomials as shown in Fig. 6.

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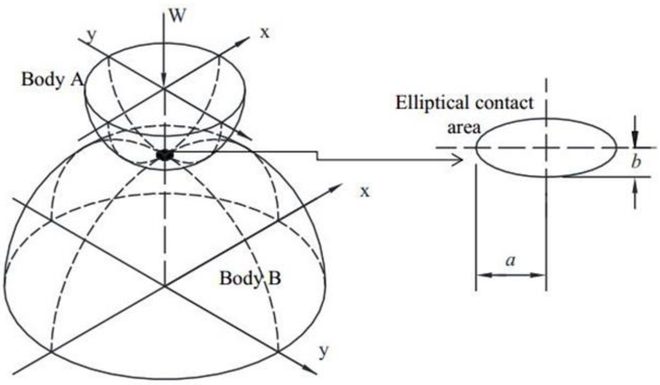

Figure. 6 Two elastic bodies with convex surface in contact [27]

Hertz proposed the solution for the determination of contact area and pressure distribution between two bodies in contact. The body surface shapes near the contact point without load may be represented by the Eq.1 and Eq.2 below.

$$Q_1(x,y) = A_1X^2 + B_1Y^2 \tag{1}$$

$$Q_2(x,y) = A_2X^2 + B_2Y^2 \tag{2}$$

The coefficients A_1, A_2, B_1 and B_2 are constants, with A_2 equals to zero since the railway track is practically straight. So therefore,

$$A = \frac{1}{2}\left(\frac{1}{R_{1y}} + \frac{1}{R_{2y}}\right) \tag{3}$$

$$B = \frac{1}{2}\left(\frac{1}{R_{1x}} + \frac{1}{R_{2x}}\right) \tag{4}$$

where R_{1x} *and* R_{1y} are principal rolling radii of the rail and wheel respectively and R_{2x} *and* R_{2y} are principal transverse radii of curvature of the rail and wheel respectively. The pressure over the contact patch is given as,

$$P(x,y) = P_o\sqrt{\left(1 - \left(\frac{x}{a}\right)^2 + \left(\frac{y}{b}\right)^2\right)} \tag{5}$$

where a is the longitudinal semi axes of the contact ellipse and b is the lateral semi axes of the contact ellipse, F is the vertical load applied normal to the contact patch, and $P_o = \frac{3F}{2\pi ab}$ is the maximum contact pressure (Hertz stress) which occurs at x=0 and y=0. The semi axis a and b are formulated as a function of material properties of contacting elements (elastic modules and poisons ratio) and constants of A and B [28].

Each vehicle in AALRT has 3 cars and each car has one bogie and each bogie has 4 wheels, so each vehicle has 12 wheels. The normal load (F) applied by the vehicle on each wheel are:

1. F= 35970 N, for empty vehicle;
2. F= 48428.7 N, for full capacity of the vehicle;
3. F= 51392.23 N, for overload capacity of the vehicle.

An additional weight is the Axle load, which is equals to 11.33 t or 111147.3 N, is applied on each wheel.

Therefore, the total normal load applied by the vehicle on each wheel and the values of *a*, *b*, P_{max} and *Po* (mean contact pressure, 0.78 P_{max}) is reported using table 4.

Table 4. Values of contact patch parameter (a, b, P_{max}, Po) at different loading conditions of the train

Lording condition	Cases	Load (N)	a (mm)	b (mm)	P_{max} (MPa)	Po (MPa)
Empty	Case 1	35970 N	9.09	2.38	793.85	619.203
Full	Case 2	48428.7 N	10.04	2.63	875.69	683.04
Overloaded	Case 3	51392.23 N	10.24	2.68	894.14	697.43

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Contact surface area, mean pressure and maximum contact pressure increases with load. In particular, as the contact surface area is expanding, the volume of material involved to contact stress during rolling sliding contact should increases that may results in a greater extent of removed materials due to wear damage. Wear is the gradual damage between materials involved in relative motion. For an unlubricated sliding condition such as the wheel or rail, the wear rate depends on the normal load, relative sliding speed, initial temperature and the thermal, mechanical and chemical properties of the material in contact [26]. Some of the factors that affect wear of rails are wheel load, speed, adhesion, material type etc. but for the purpose of this analysis, we shall be considering the effects of speed and wheel load on the wear of the rail material.

3. Results and Discussions

In this research work the effect of loading conditions, running speed and coefficient of friction on the wear parameters of rails of Addis Ababa light railway were investigated. The results of the simulation will be given in specific wear rate (mm3/N m) instead of wear rate (volume loss per unit sliding distance, mm3/m) since wear rate is load independent and also Specific wear rate is more accurate description of the wear characteristics of any materials, particularly for steel materials [29].

It is used as a precise indication of the wear properties of the sliding bodies under loads, speeds, and sliding distance or time. Simulation of vehicle model is conducted using SIMPACK. The model was simulated for about 20 seconds with different maximum mean Hertzian pressure of: 619.203 MPa, 683.04 MPa and 697.43 MPa and sliding distance of 111.2 m, 194.4m and 388. 9 m. Effects of vehicle load on wear rate of rails.

3.1. The effects of coefficient of friction and wheel load on wear rate of rails

From Fig. 7 (a) to Fig. 7 (c), it can be seen that, the wear rate reduces as the applied wheel load reduces. It reduces by a magnitude of 10-1, the highest specific wear rate is recorded at a COF of 0.5 for the overload capacity when the vehicle is running at its maximum operating speed while the lowest specific wear rate is recorded at a COF of 0.1 when the vehicle is running at 20 Km/h. Fig. 7 represents the coefficient of friction against specific wear rate at different loading capacity of the train.

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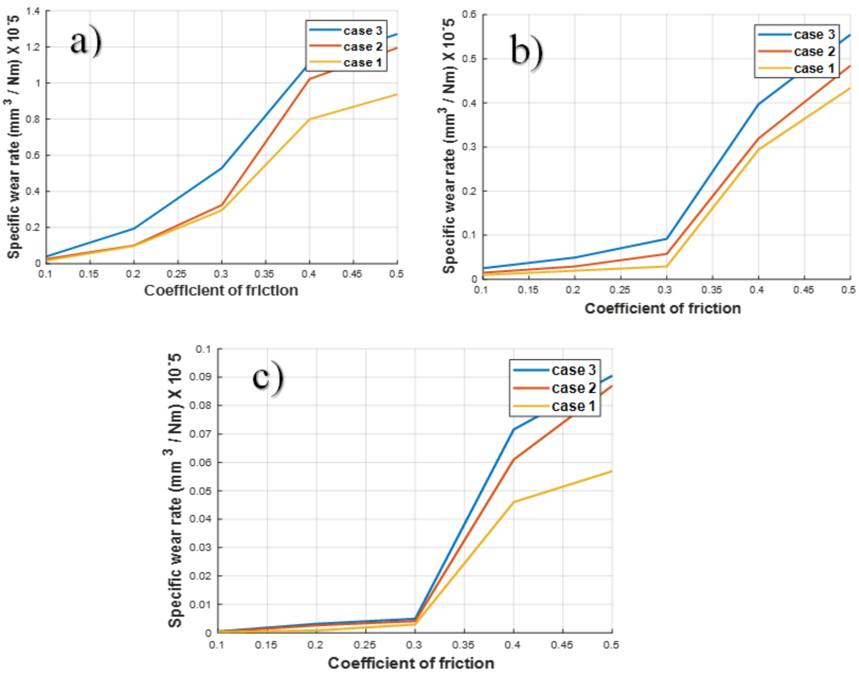

Figure. 7 Specific wear rate against coefficient of friction at different running speeds of a) 70 Km/hr; b) 35 Km/hr; and c) 20 Km/hr

In the case of empty train (case 1), the wear rate significantly increases as the coefficient of friction between the train wheels and rails increases. In addition, loading conditions variation affects the specific wear rate and as the load increases from empty to full then again to overloading conditions, the deviation of the corresponding wear rates are increasing in particular at a higher coefficient of frictions. Fig. 7 (b) and (c) have similar trends with Fig 7. (a) for the selected vehicle speed cases. For the 20Km/hr vehicle speed, the specific wear rate increase slightly until the COF is 0.3 afterwards, it increases significantly until the COF is 0.4, and then the increment is at the continuous. For the 35 Km/hr vehicle speed, the trend is almost similar with the 20 Km/hr case. For the 70 Km/hr case, the specific wear rate increases almost linearly till it reaches a COF value of 0.4, after which, there is a sharp increment upwards. This results tends to agree with the work done by [30] as it reports the effect of vehicle load on wear rate.

3.2. The effect of Vehicle speed on wear rate of rails

The specific wear rate due to time increases slightly as vehicle speed increases. This is due to the changes coming from friction heating between the wheels and the train.

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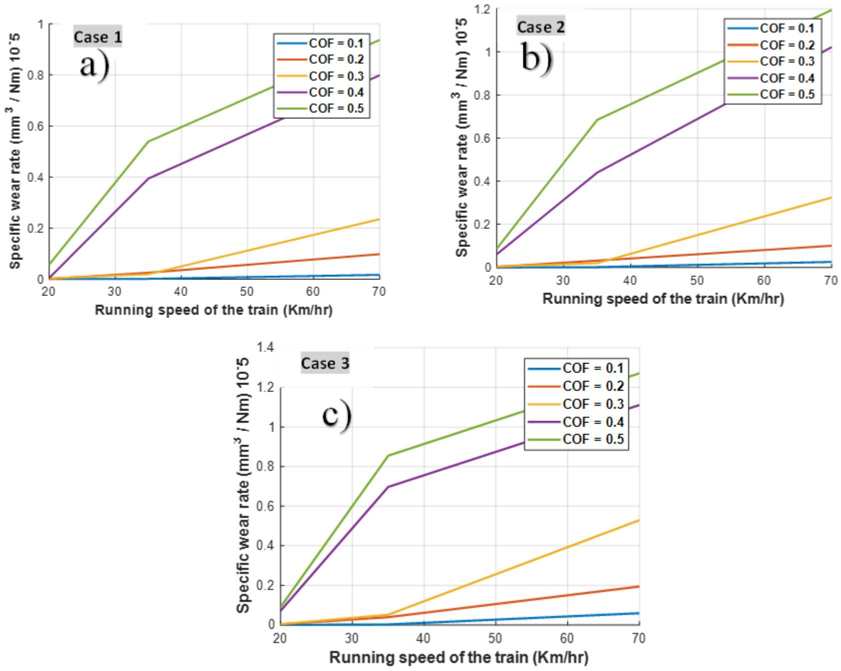

Figure. 8 Specific wear rate against Vehicle speed

From the variation of specific wear rate against running speed of the train follows similar trends. It can be seen that there is a slight increment in the specific wear rate for coefficient of friction values of 0.1, 0.2 and 0.3 but as the COF exceeds 0.3, the specific wear rate becomes very high, this is due to the fact that there is an increment in vehicle speed. When the coefficient of friction is constant, as the speed increases, the specific wear also increases and vice versa. It is worthy to note that as the vehicle speed and COF increases, the Specific wear rate increases, thus maintaining appropriate vehicle speed and normal wheel load levels can reduce coefficient of friction and in turn reduce wear and improve the railway rails. According to [31], in his experiment of unlubricated sliding for AISI 1045 carbon steel pins, he opined that the specific wear rate are categorized into two groups namely; mild and severe wear type. For the mild wear type, the specific wear rate is in the range of (10^{-7} to 10^{-4} while the severe wear type is in the range of 10^{-3} mm^3/Nm). He agreed that the specific wear rate decreases with a decrease in speed. This result tends to agree with his in the sense that the specific wear rate of the AALRT rails is in the range of 10^{-5} mm^3/Nm.

3.3. Effect of sliding distance on Wear rate of rails

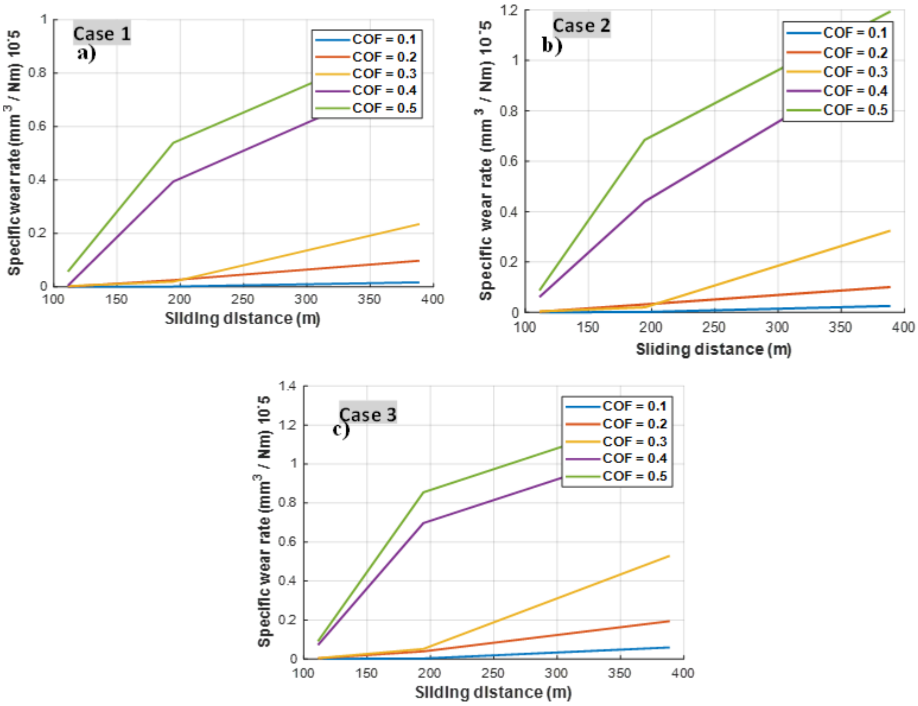

Figure. 9 Effect of different loading conditions and sliding distance on wear rate

Fig. 9 (a) to Fig. 9 (c) shows the effect of sliding distance on the specific wear rate of the rail. In Fig. 9(a), the sliding distance at which the specific wear rate was maximum was at 388.9 m and the sliding distance at which the specific wear rate was minimum was at 111.2 m. This shows that as the sliding distance increases, the specific wear rate increases and vice versa. As the loading capacity of the train increases, the curves dips outwards as shown in Fig. 9c. The coefficient of friction has an effect on the sliding distance as it affects the specific wear rate of rails. At higher sliding distance, the specific wear rates increase and at lower sliding distance, the specific wear rate reduces. According to the wear studies by [31]–[34], they all agreed that the wear performance of steel materials deteriorates with increase in the sliding distance which validates the results in this study.

3.4. The effect of sliding distance on volumetric loss of rails

The volumetric loss of the rail material reduces as the sliding distance reduces and increase as the sliding distance increase. From fig. 10(a) and fig. 10(b), it can be seen that as the coefficient of friction increases, the curve becomes more linear, this is due to the high velocity values. This results tends to agree with that of [11] in his experiment involving the investigation of wear properties of rails. He agree that the wear volume of the rail roller increases rapidly with the increase of axle load.

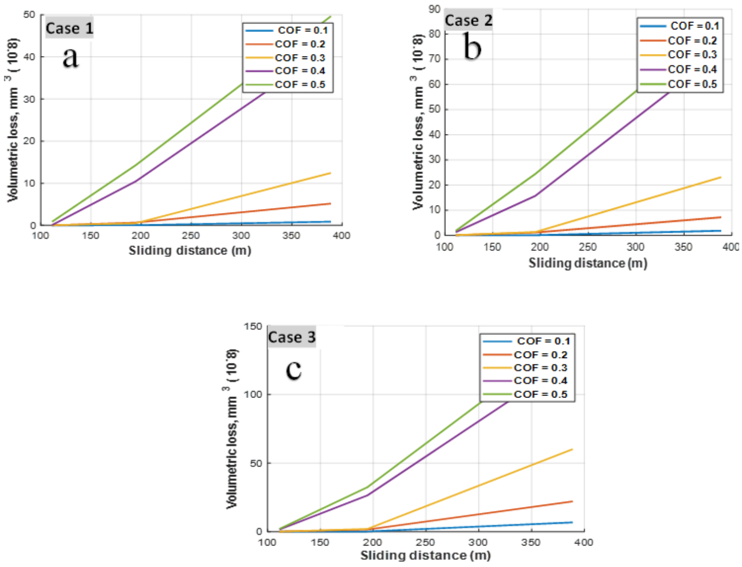

Figure. 10 Volumetric loss at different loading capacities of the train

3.5. Result comparison

The result in this study is in agreement with work the done by Windarta [35] and also with the study done by Kato [31] on the friction and wear of passive metals and coatings. The contact pressure result is also in line with the work of Pau, et al. [36].

4. Conclusion

The wear behavior of Addis Ababa light rail transit rails was studied. The effects of coefficient of friction, wheel load and vehicle speed was investigated. The following conclusions was drawn on completion of the research;

- ✓ The highest specific wear rate occurred at the maximum operating speed of the train (70 Km/hr.) while the lowest specific wear rate occurred at a speed of 20 Km/h. this shows that as the running speed of the train increases, the specific wear rate increases.
- ✓ The highest wear rate of the rail occurred at the overload capacity of the train.
- ✓ The specific wear rate of rails slightly increases as the coefficient of friction increases.
- ✓ The coefficient of friction has an effect on the sliding distance as it affects the specific wear rate of rails. At higher sliding distance, the specific wear rates increase and vice versa.
- ✓ The lower the running time of the train, the lower the specific wear rate of the rail.
- ✓ At constant coefficient of friction. As the wear rate is reducing, the volumetric loss is increasing.
- ✓ The wear rate of rails reduces as the applied wheel load reduces. So in other to increase the wear life of the rails, it is imperative to use medium friction coefficient values and operate the train between the speed ranges of 20 to 40 Km/hr.

4.1. Recommendation

The specific wear rate significantly increases as the wheel load increases. Also, small coefficient of friction values, together with increase in vehicle speed, wheel load and sliding over long distances, reduces wear rate. So by maintaining appropriate train speed within the range of 20 to 40 Km/hr and by using small coefficient of friction values we can reduce frictional force and wear and also improve railway infrastructure, thereby making last for the required duration.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The raw/processed data required to reproduce these findings cannot be shared at this time due to legal or ethical reasons. The raw/processed data required to reproduce these findings cannot be shared at this time as the data also forms part of an ongoing study.

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