REVIEW OF MECHANICAL WEAR MODELS

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Abstract

The wear modelling is of fundamental issue in the industrial field, mainly correlated to the economy and safety. Therefore, there is a need to study the wear models and wear estimation. This paper introduced the literature review for mechanical wear models. The function of wear models is to predict the rate of material removal from the surface. Classical wear theory begins by considering the rate of material removal as a function of some parameters such as load, sliding speed, sliding distance and hardness of material. In sliding wear models there are more than 100 different variables and constants. These models contains between two to twenty six variables in a single equation. Unfortunately, some constants are assigned to represent specific quantitative phenomena which are not readily measurable such as surface strength, and fatigue life of an asperity. Between 1957 and 1992, that there were 182 wear equations for the several types of wear. The most important issue of the 182 equations is that it include on a great number of variables. Each author combines a different array of variables, often for the same mechanical system.

Keywordsmechanical wear models, review, classical wear theory, computer simulations.

1.INTRODUCTION

Wear is usually defined as the removal of material from contacting surface by mechanical action [1]. Wheel wear and rail wear are the loss of material from the contacting surface due to rail/wheel interaction. Rail wear is dependant on several parameters such as axle load, train speed , wheel material type, rail material type, curvature, traffic type, lubrication, and environmental conditions [2]. Wheel wear is one of the most significant problems affecting the cost and performance of railway transportation systems [1]. Wheel and rail wear is a significant issue in railway systems. Accurate prediction of this wear can improve economy, ride comfort, prevention of derailment and planning of maintenance interventions. Poor prediction can result in failure and consequent delay and increased costs if it is not controlled in an effective way. However, prediction of wheel and rail wear is still a great challenge for railway engineers and operators.

2.REVIEW OF WEAR MODELS

Reye in 1860 considered that the volume of material removed from a body was proportional to the energy dissipated into it by the relative motion of the two contacting surfaces such as shown in the following equation[3], [4], [5].

$$V = K_R W \qquad (1)$$

Where Vthe volume of material is removed, K_R is Reye's wear constant and W is the work dissipated into the material. Reye's approach was one of the primarily methods to calculate the wear in terms of energy dissipated.

Holm in 1946 considered that the process of wear with regard to the relative motion of surface asperities. He suggested that the individual atoms on opposite asperities were moving towards each other and colliding. His suggestion stated that the wear was a function of the properties of the materials in contact and the load applied over the contact such as shown in the following equation [7],[3], [6],[8].

$$V = Z \frac{p}{p_m} \tag{2}$$

In the above equation V is the volume of material removed per unit sliding distance, Z is the probability of removal of an atom per atomic encounter and would depend on the properties of the materials in contact, p is the load applied, and p_m is the flow pressure of a worn surface “hardness of material”.

Burwell and Strang suggested that the volume of wear material can be calculated using the following equation [6]:

$$Q = k \frac{W\,d}{H} \tag{3}$$

Where k is the probability of removing wear particles, W is the load, d is the sliding distance, and H is the hardness of material. Thus the wear volume per unit sliding distance w is [6]:

$$w = k \frac{W}{H} \tag{4}$$

Archard in 1953 studied the wear process and suggested that there were a number of key considerations that must be included in a wear model. Archard has referenced Holm in his publications and his work could be thought of as an extension or furthering of Holm’s wear equation. Archard assumed that two rough surfaces are in discrete contact “The contact consists of individual spots”. The area of each spot expands from zero to maximum $\pi\, a^2$,and then shrinks back to zero such as shown in Figure 1. Normal load can determined by the following equation [3], [9]-[11]:

$$p_n = \pi\, a^2 p_m \tag{5}$$

Where : p_m is the yield pressure of a plastically deformed asperity, and a is the contact spot radius.

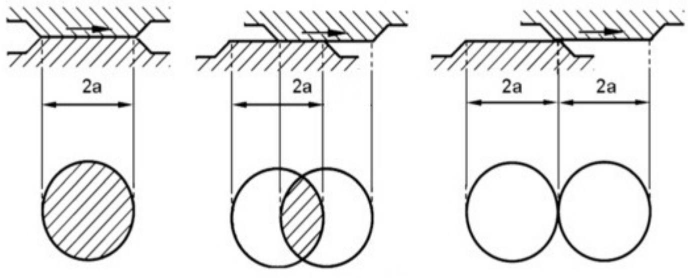

Figure 1: Archard wear model[9], [11]

Assume that this volume consists of a half-sphere of radius a, the volume is given by:

$$V_n = \frac{2}{3} \pi a^3 \quad (6)$$

Wear rate (per unit distance of sliding) is given by:

$$i_n = \frac{V_n}{2\,a} \quad (7)$$

Then:

$$i_n = \frac{\pi\, a^2}{3} \quad (8)$$

Therefore:

$$i_n = \frac{P_n}{3\ P_m} \quad (9)$$

The total wear rate would be equal to the total contribution from all contact spots:

$$I^{*} = \sum i_n = \frac{P}{3\ P_m} \quad (10)$$

Where the total normal load on the contact is:

$$P = \sum P_n \quad (11)$$

Archard assumed that the wear can be calculated using the following equation:

$$I = k\, I^{*} \quad (12)$$

Where k is constant.

It is written as:

$$I = \frac{k\,P}{3\,P_m} \quad (2.13)$$

It is convenient to designate $K = \frac{k}{3}$ and assume that $P_m = H$.

Then the equation of wear develops in the form:

$$I = \frac{K\,P}{H}\ \ (mm^3/mm) \quad (14)$$

Where: I is the volume worn per unit sliding distance (wear rate), P is the normal load, H is the hardness of the softer material, and K is the wear coefficient.

Then Archard expressed the wear equation such as shown in the following form: [3], [6], [7].

$$V = k\,\frac{N\,S}{H}\ \ (mm^3) \quad (15)$$

Where: V is the volume of wear (mm^3), k is the wear coefficient (-), N is the normal load (N), S is the sliding distance (mm), and H is the hardness of material (N/mm^2).

The wear coefficient (k) can calculated using the following equation [1], [12], [13]:

$$k = \frac{V\,H}{L\,F_N} \qquad (16)$$

Where: kis the non-dimensional wear coefficient, Vis the volume of wear (mm^3), H is the hardness of material (N/mm^2), F_N is the normal load (N) and Lis the sliding distance (mm). The wear coefficient k is dimensionless and always less than 1 [9], [14].

The values of wear coefficient k for various materials against steel under dry conditions using pin-on-disc tests are illustrated such as shown in Table 1.

Table 1:Wear coefficient values [14]

Material	k
Mild steel (on mild steel)	7×10^{-3}
α/β brass	6×10^{-4}
PTFE	2.5×10^{-5}
Copper–beryllium	3.7×10^{-5}
Hard tool steel	1.3×10^{-4}
Ferritic stainless steel	1.7×10^{-5}
Polythene	1.3×10^{-7}
PMMA	7×10^{-6}

Wear coefficient k for unlubricated surfaces is shown in Table 2.

Table 2:Wear coefficient unlubricated surfaces [15]

Material combination	k
Low carbon steel on low carbon steel	70×10^{-4}
60/40 Brass on tool steel	6
Teflon® on tool steel	0.25
70/30 Brass on tool steel	1.7
Lucite on tool steel	0.07
Molded bakelite on tool steel	0.024
Silver steel on tool steel	0.6
Beryllium copper on tool steel	0.37
Tool steel on tool steel	1.3
Stellite #1 on tool steel	0.55
Ferritic stainless steel on tool steel	0.17
Laminated bakelite on tool steel	0.0067
Tungsten carbide on low carbon steel	0.04
Polyethylene on tool steel	0.0013
Tungsten carbide on tungsten carbide	0.01

The wear coefficient depends on several parameters such as a contact pressure, sliding velocity, and temperature and the degree of lubrication in the contact area, therefore, it is a very complex parameter to determine. A wear map can used to describe the wear coefficient as a function of contact pressure and sliding velocity. Each wear map corresponds to a certain rail and wheel material (The rail and wheel are assumed to have similar material properties). Figure 2 shows a wear map which is describes four approximate regions, in this chart, the contact pressure limit at 0.8H corresponds to 80% of the hardness, and the wear coefficient depends on the sliding velocity [16].

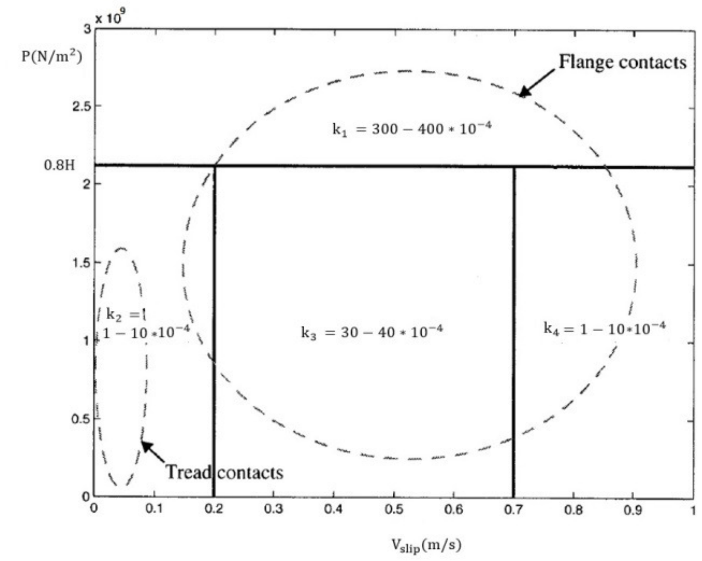

Figure2:Wear chart for the wear coefficient [16]

Montgomeryet al., [3] stated that “there are a number of problems with the assumption that the wear rate is directly proportional to the load, as stated by Archard. The surface characteristics of the materials in contact will be changing as a result of material being removed, they will generally become rougher and therefore a change in the friction coefficient by a factor of two or three could result in a change of the rate of wear by one or more orders of magnitude”.

The weakness of using the Archard model for wear modelling is that it depends on the proper calculation of wear coefficient k, where the wear coefficient k is a very complex parameter to determine, if k is not calculated correctly, it will lead to inaccurate results of wear modelling.

The Royal Institute of Technology Stockholm (KTH) developed the following wear model based on the Archard model. The volume of worn material is written as:

$$V = K_A \frac{P\ S}{H} \tag{17}$$

Where: V is the volume of wear in (mm^3), Sis the sliding distance in (mm), Pis the normal force in (N), His the hardness of the softer material in (N/mm^2), and K_A is wear coefficient. The values of wear coefficient K_A which shown in Table 3 were obtained using a pin-on-disc test, and a twin disc test rig using different materials. Where p is the contact pressure and $\dot{S}$ is the slip velocity [17], [18].

Table 3:Wear coefficient (KTH) [17], [18]

Pressure p[GPa]	Slip velocity $\dot{s}$[m/s]	K_A[-]
$p > 2.1$	any $\dot{s}$	$300 - 400.10^{-4}$
$p < 2.1$	$\dot{s} \geq 0.2$	$1 - 10.10^{-4}$
$p < 2.1$	$0.2 \leq \dot{s} < 0.7$	$30 - 40.10^{-4}$
$p < 2.1$	$\dot{s} \geq 0.7$	$1 - 10.10^{-4}$

The University of Sheffield (USFD) developed the following wear model. The wear function developed by the USFD relates to the wear rate, which expresses the weight of lost material (μg) per distance rolled (m) per contact area A(mm^2), to the wear index Tγ as follow [18]:

$$\text{Wear rate } = K \frac{T\gamma}{A} \tag{18}$$

Where: K is wear coefficient, and Tis the creep force, γis the slip, and A is the contact area.

The wear equations presented by the USFD are shown in Table 4. This formulation was developed using twin disc rig experiments. The USFD wear function was developed for wheel (R8T) and rail (UIC60 900A) materials.

Table 4: The USFD wear function [18]

Wear regime	Wear range $\frac{T\gamma}{A}$ (N/mm^2)	Wear rate (μg/m/mm^2)
Mild	$\frac{T\gamma}{A} < 10.4$	$5.3\,\frac{T\gamma}{A}$
Severe	$10.4 \leq \frac{T\gamma}{A} < 77.2$	55.0
Catastrophic	$\frac{T\gamma}{A} \geq 77.2$	$61.9\,\frac{T\gamma}{A}$

The Royal Institute of Technology Stockholm model and the University of Sheffield model can be used for wear modelling, but this is also dependent on the correct calculation of the wear coefficient k.

British Rail Research (BRR) developed equations to describe wear behavior as shown in Table 5. Wear is calculated as material loss expressed in mm^2 of lost area from any radial section through the profile per km rolled. Where: Tis the creep force (N), γ is the creepage [-], and D is the wheel diameter in (mm) [17],[19]. These equations were obtained from twin disc tests on R8T (wheel) and BS11 (rail) steels.

Table 5:Equations of the BRR wear function [19]

Friction	Regime	Tγ (N)	Wear Rate (mm2/km rolled)
Dry	Mild	< 100	0.25Tγ/D
Dry	Mild Plateau	> 100 and < 200	25.0/D
Dry	Severe	> 200	(1.19Tγ - 154)/D

The British Rail Research model can be used for wear modelling, but the main limitation of the BRR wear model lies in the fact that the equations given in Table 2.5 are only valid for the specific materials considered.

R. Lewis and U. Olofsson[1] presented an approach which can be used for wheel wear modelling (expected wear proportional to wear indexWI) as provided bellow:

$$WI = K(T_1\gamma_1 + T_2\gamma_2) \tag{19}$$

Where K is the constant, T_1, T_2 are the longitudinal and lateral creep forces respectively, and γ_1, γ_2 are the longitudinal and lateral creepages respectively. This relationship between the energy dissipation and material removal can be used to predict wheel/rail wear. This model is one of the most common models which have been used in recent works for wear modelling; accordingly, it has the same drawbacks as most of the classical wear models, which are dependent on the value of certain constants.

The American Society for Testing and Material (ASTM) developed a wear model which can be used to model the pin wear and disc wear for pin-on-disc experiments as shown in the following equations [20], [21], [22]:

$$\text{Pin volume loss} = \frac{\pi\, h}{6}\left[\frac{3\, d^2}{4} + h^2\right](mm^3) \tag{20}$$

The height of material removed for pin (h) is given by:

$$h = r - [\, r^2 - \frac{d^2}{4}\,]^{0.5}(mm) \tag{21}$$

Where: d is the pin wear scar diameter, and r is the pin radius.

$$\text{Disc volume loss} = 2\,\pi\, R\,[\, r^2 \sin^{-1}\left(\frac{d}{2r}\right) - \left(\frac{d}{4}\right)(4\, r^2 - d^2)^{0.5}]mm^3 \tag{22}$$

Where:R is the disc wear track radius, r is the pin radius, and d is the disc wear track width.

The accuracy of pin/disc wear modelling using the ASTM model is dependent on the proper measurements of the pin wear scar dimensions and disc wear scar dimensions, this requires an accurate instrument. The ASTM model has a limitation however, it can only be used to model the pin/disc wear, but it cannot be used for wheel and rail wear modelling.

In the survey of the wear modelling equations, many equations were found for wear modelling; for example, [23] presented 28 equations for erosion wear modelling, and a couple of equations for sliding wear modelling; the problem with these models is that they depend on different variables and constants.

The modelling of wear can be carried out with mathematical models and computer simulations [7]. The railway wheel wear prediction is a very significant problem in railway systems. In the past, the reprofiling intervals of railway wheels have been planned according to designer's experience. Today, computer simulation tools can be used to predict the wheel wear [24].

3. Review of the computer simulations for wheel/rail wear prediction

The following sections present a review of using the computer simulations for wheel/rail wear prediction.

Pearce and Sherratt [25] presented a model which is shown in Figure 3 to predict the wheel wear. VAMPIRE software was used to simulate the dynamics of the railway vehicles. The wear algorithm is shown in Table 6, the material lost is proportional to the energy dissipated in the contact zone. For wheel wear prediction, two track inputs were selected from VAMPIRE input files, it is a straight track and a curved track. The P8 wheel profile and P11 wheel profile were used in this study. The position of the contact on the wheel, creepage, and creep forces are correlated and summed to calculate the material loss distribution across the wheel profile. The contact patch data were recomputed before each journey and then this step was repeated until a desired mileage was achieved.

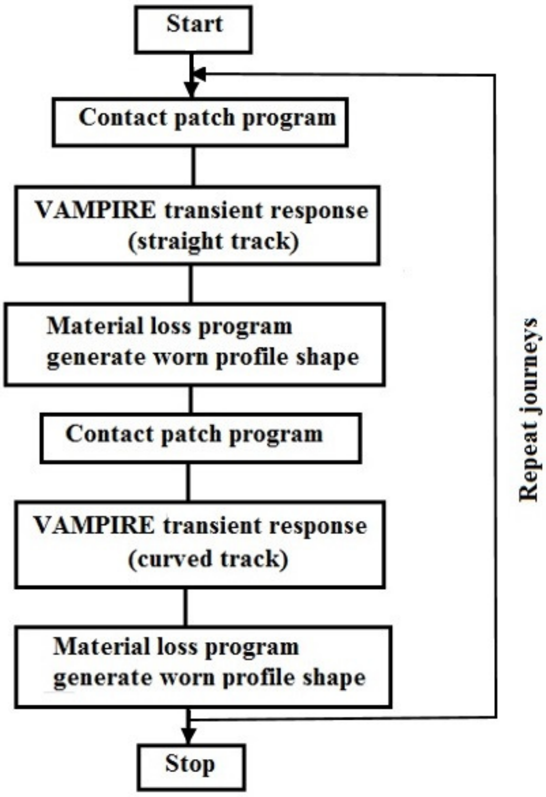

Figure 3:Wheel wear prediction model [25]

Table 6:Wear algorithm [25]

$T\gamma < 100N$	material loss $0.25\,T\gamma/D$
$100 \leq T\gamma < 200N$	material loss $25.0/D$
$T\gamma \geq 200N$	material loss $(1.19T\gamma - 154)/D$

Where T is the creep force (N), and γ is the creepage [-], and D is the wheel diameter in (mm).

Shu et al., [26] used a NUCARS vehicle/track multibody simulation program to estimate the rail wear. The advantage of NUCARS is that the rail profile can be modified online based on wear index (Tγ) and the rail profile is automatically updated for the next run. The rail wear model is shown in Figure 4. A wheel database, consisting of new wheel profiles, little worn wheel profiles, and heavy worn wheel profiles. This to reflect the effects of wheel shape on wear. The rail wear predicted using NUCARS model was validated using rail wear test results. The simulation predictions were very close to the test results.

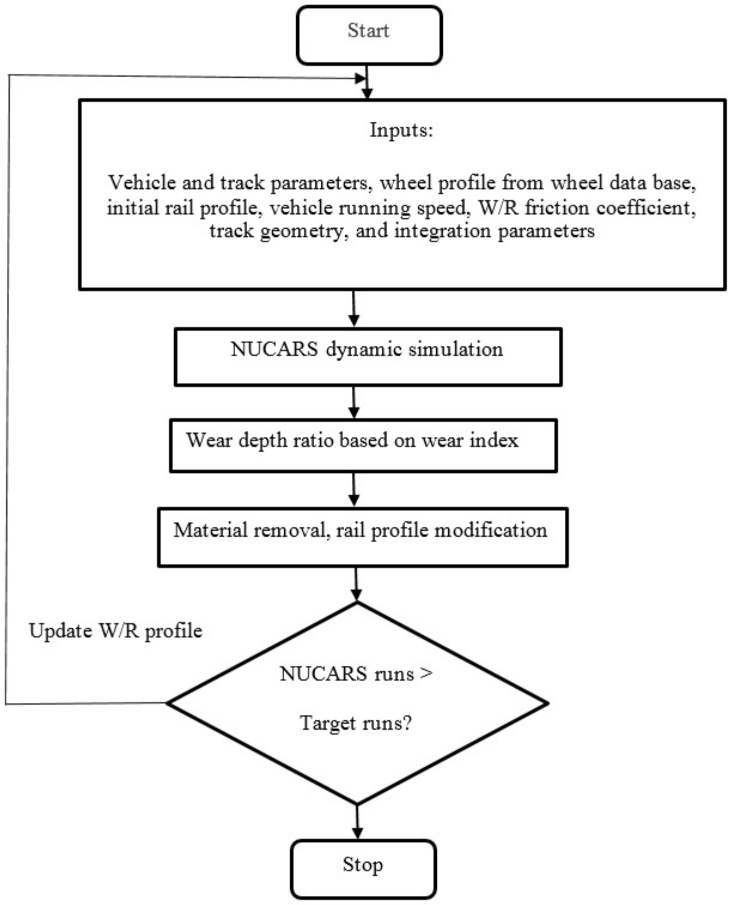

Figure 4: Rail wear simulation procedures in NUCARS [26]

Ward et al., [27] presented a model to predict the wheel wear as shown in Figure 5 and Table 7. To generate the wear coefficients (k) for the model, a twin disc test was carried out. The approach for wheel wear prediction in this model is based on a wear index. The wear rate was calculated using the following equation:

$$\text{Wear rate} = k\,\frac{T\gamma}{A} \tag{23}$$

Where A is the contact area, T is tractive force, and γ is slip at the wheel/rail interface.

Multi-body dynamics simulations of a railway wheelset were carried out using ADAMS/Rail software. The wheel profile was discredited into strips and the wear was determined for each strip. The worn wheel profile is then fed back to the ADAMS/RAIL to update the wheel profile to predict the wheel wear.

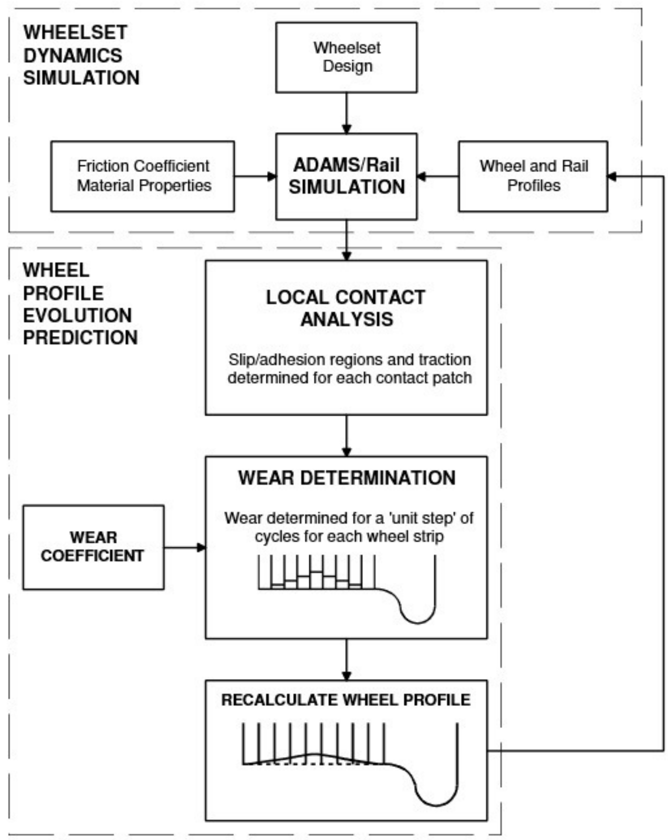

Figure 5:Railway wheel wear modelling scheme [27]

Table 7: Wear regime

Regime	$\frac{T_Y}{A}$ (N/mm^2)	Wear rate (μg/m/mm^2)
k_1	$\frac{T_Y}{A} < 10.4$	$5.3\ \frac{T_Y}{A}$
k_2	$10.4 < \frac{T_Y}{A} < 77.2$	55
k_3	$77.2 < \frac{T_Y}{A}$	$61.9\frac{T_Y}{A}$

Enblom [28] presented a model for wheel wear prediction as shown in Figure 6. A commercial Multibody Software (MBS) was used to simulate the dynamics of the railway vehicles. The wheel wear was calculated using the Archard wear model. The wear coefficient was determined using a wear chart, where the value of wear coefficient is a function of contact pressure and sliding velocity. Laboratory tests (twin disc test rig and pin-on-disc rig) were used to determine the wear coefficient. In this paper, the wheel wear was predicted using MBS simulation tool. The wheel wear predicted has been validated by comparing it to wheel wear measured (Stockholm commuter network).

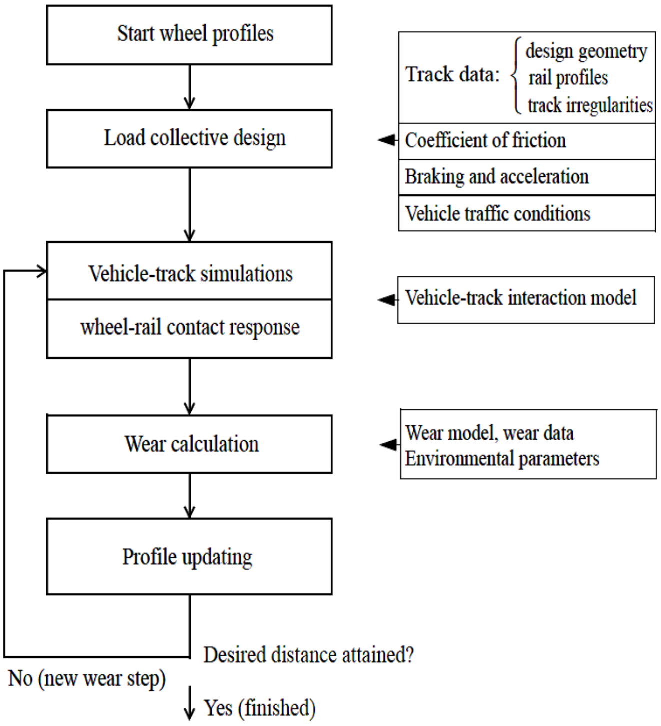

Figure 6: Wheel wear prediction model [28]

Pombo et al., [24] presented a model to predict the wheel wear as shown in Figure 7. A commercial Multibody Software (MBS) software was used to simulate the dynamics of the railway vehicles. The MBS tool was applied in this paper in order to assess the effect of primary suspension stiffness,rail cant, traction/braking forces, and vehicle velocity on wheel wear. The wear was calculated using the energy dissipated in the wheel-rail contact.

Pombo et al., [29] presented a model to predict the wheel wear as shown in Figure 7. The MBS was used to simulate the dynamics of the railway vehicles. The MBS was applied in this paper in order to show the capabilities of MBS computational tool for wear prediction by evaluating the effect of trainset design, track layout, friction conditions, and wheel flange lubrication on wear. The wheel wear was calculated using the energy dissipated in the wheel-rail contact.

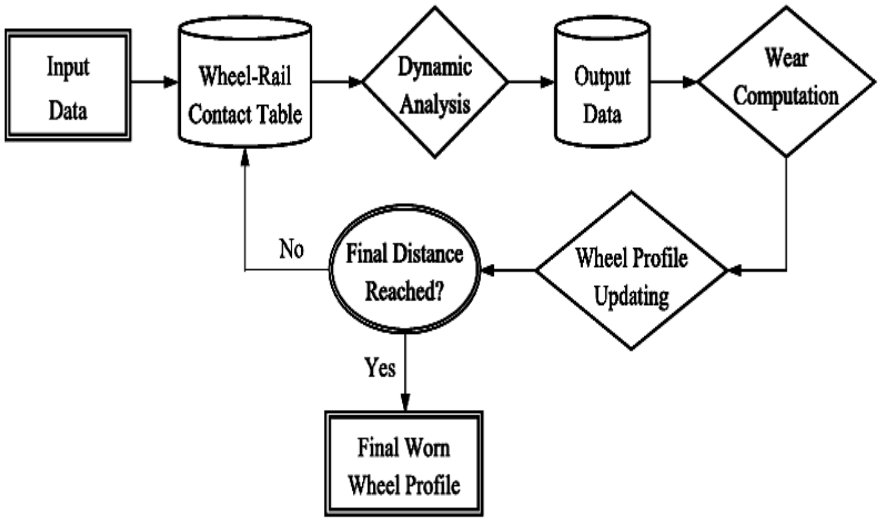

Figure 7:Schematic representation of wear prediction [24], [29]

Bevanet al., [30] provided a model to predict wheel wear. The methodology of wheel wear prediction is shown in Figure 8. VAMPIRE vehicle dynamics software was used to simulate the dynamics of the railway vehicles. The VAMPIRE software generated the wheel-rail contact data and forces, these forces and wheel/rail contact data were used as inputs to the model to predict wear. This procedure is used to update the wheel profile, and the volume of material removed was determined using the Archard wear model and energy model. The wear coefficient (k) was determined from a map of wear for wheel/rail steels.

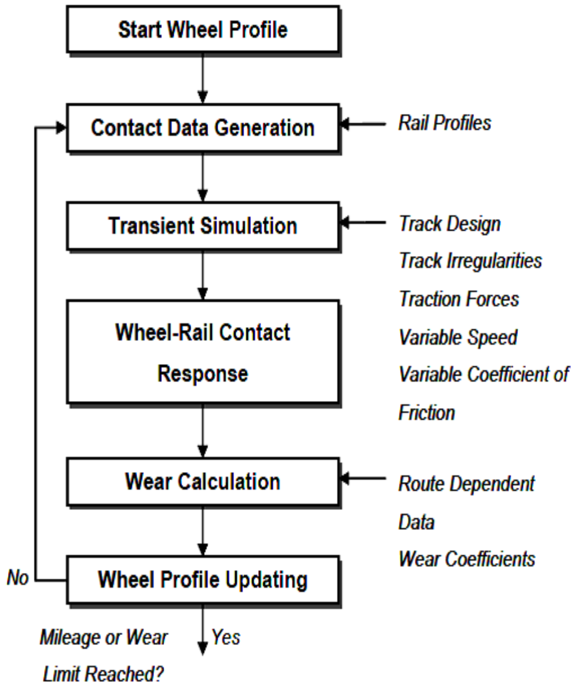

Figure 8:Methodology of wheel wear prediction [30]

Arandojo [31] presented a model for wear prediction as shown in Figure 9. The GENSYS software was used in this paper to predict railway wheel wear. The track type, running distance, and type of rail and wheel profiles were loaded to the model as inputs. The vehicle-track interaction is performed in GENSYS software. The wear was calculated based on the Archard law. The GENSYS software is a three-dimensional general multi-body-dynamics program. Several simulations were carried out to predict the railway wheel wear of the first wheelset. A passenger vehicle was used in simulations, it consists of a single carbody with two bogies, four wheelsets and eight wheels.

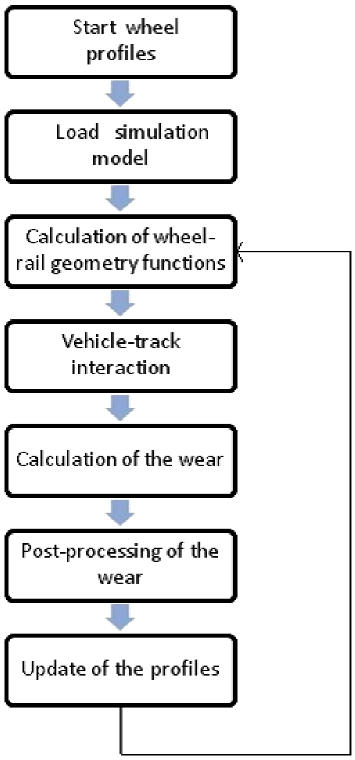

Figure 9:Wheel wear prediction model [31]

Tanifuji [32] used SIMPACK software for wheel wear prediction. The lateral movement of the wheel/rail contact patch and the energy dissipated (Tγ) between wheel and rail were used to estimate the wheel wear as shown in Figure 10. Simulation tests were carried out on a straight track and on a curved track to predict the wheel wear. The running distance was 268000 km. Comparisons between wear predicted using SIMPACK software and wear measured were carried out to validate the wheel wear on flange and on tread. The results showed that the wear predicted using SIMPACK software was very close to the wear measured.

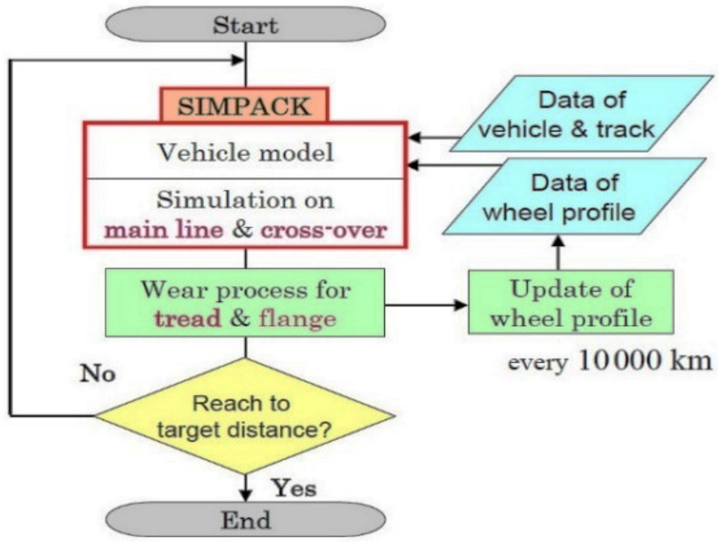

Figure 10:Flow chart for wear prediction [32]

A Nonlinear Autoregressive model with eXogenous input neural network (NARXNN) was developed to predict the wheel and rail wear for the twin disc rig experiments[33]. The NARXNN was used to predict wheel wear and rail wear under deferent surface conditions such as dry, wet, lubricated, and sanded conditions. The neural network model was developed to predict wheel wear in case of changing parameters such as speed and suspension parameters. VAMPIRE vehicle dynamic software was used to produce the vehicle performance data to train, validate, and test the neural network. Three types of neural network were developed to predict the wheel wear: NARXNN, backpropagation neural network (BPNN), and radial basis function neural network (RBFNN).

4. Conclusion

Regarding the literature review, two basic types of wear models have been used for wear modelling: sliding models such as Archard wear model, and energy transfer models. The Archard wear model is the most frequently used for wear modelling in practical engineering applications; once the wear coefficient is obtained, the amount of wear can be simulated. The American Society for Testing and Material (ASTM) developed a model which can be used for pin wear and disc wear modelling for a pin-on-disc test.

The computer simulation packages such as VAMPIRE, ADAMS/Rail, GENSYS, Multibody Software (MBS), SIMPACK, and NUCARS together with the models which were shown in this review are very useful tools to study railway wheel/rail wear. The software packages have some advantages, for example, the ADAMS has the advantage of a strong Graphical User Interface (GUI). This means the users can see exactly what they are constructing on the screen in a 3-dimensional form, which can be manipulated around a variety of axis and all the necessary functions can be accessed from the menu system. With respect to this review, it can be noticed that the wear was calculated using either Archard's model or the energy dissipated model. The computer modelling of railway vehicle dynamics can be performed using a number of different commercial software packages.

Artifical neural networks developed to predict the wheel and rail wear for the twin disc rig experiments, and to predict wheel/rail wear under deferent surface conditions such as dry, wet, lubricated, and sanded conditions. The neural network model was developed to predict wheel wear in case of changing parameters such as speed and suspension parameters.

References

[1] R. Lewis and U. Olofsson, *Wheel-rail interface handbook*: Elsevier, 2009.

[2] V. Reddy, "Development of an integrated model for assessment of operational risks in rail track," Queensland University of Technology, 2007.

[3] S. Montgomery, D. Kennedy, and N. O'Dowd, "Analysis of wear models for advanced coated materials," 2009.

[4] E. Mönch, "Zur elementaren Theorie der Zapfenreibung," *ZAMM‐Journal of Applied Mathematics and Mechanics/Zeitschrift für Angewandte Mathematik und Mechanik,* vol. 31, pp. 94-94, 1951.

[5] A. Carpinteri and N. Pugno, "Evolutionary fractal theory of erosion and experimental assessment on MIR space station," *Wear,* vol. 257, pp. 408-413, 2004.

[6] B. Majumdar, *Introduction to tribology of bearings*: S. Chand Limited, 2008.

[7] A. Zmitrowicz, "Wear patterns and laws of wear–a review," *Journal of theoretical and applied mechanics,* vol. 44, pp. 219-253, 2006.

[8] C. R. Á. da Silva and G. Pintaude, "Uncertainty analysis on the wear coefficient of Archard model," *Tribology International,* vol. 41, pp. 473-481, 2008.

[9] M. Braunovic, N. Myshkin, and V. Konchits, *Electrical contacts: fundamentals, applications and technology*: CRC press, 2010.

[10] K. Corp., "Digital Microscope VHX-500 Series " in*http://www.keyence.com/*, ed. Japan, 2016.

[11] A. Azushima, *Tribology in Sheet Rolling Technology*: Springer, 2016.

[12] A. A. Tseng, *Tip-Based Nanofabrication: Fundamentals and Applications*. USA Springer, 2011.

[13] G. E. Totten, *Handbook of Lubrication and Tribology: Volume I Application and Maintenance* vol. 1: CRC Press, 2006.

[14] J. Williams, "Wear modelling: analytical, computational and mapping: a continuum mechanics approach," *Wear,* vol. 225, pp. 1-17, 1999.

[15] E. R. Booser, "CRC handbook of lubrication. Theory and practice of tribology: Volume II: Theory and design," 1984.

[16] A. Orvnäs, "Simulation of rail wear on the swedish light rail line Tvärbanan," 2005.

[17] N. Tassini, X. Quost, R. Lewis, R. Dwyer-Joyce, C. Ariaudo, and N. Kuka, "A numerical model of twin disc test arrangement for the evaluation of railway wheel wear prediction methods," *Wear,* vol. 268, pp. 660-667, 2010.

[18] J. Pombo, J. Ambrosio, M. Pereira, R. Lewis, R. Dwyer-Joyce, C. Ariaudo*, et al.*, "Development of a wear prediction tool for steel railway wheels using three alternative wear functions," *Wear,* vol. 271, pp. 238-245, 2011.

[19] J. Tunna, J. Sinclair, and J. Perez, "The development of a wheel wear and rolling contact fatigue model," 2007.

[20] ASTM, "Standard Test Method for Wear Testing with a Pin-on-Disk Apparatus," *Annual Book of ASTM Standards, G99-05,* vol. 3, 2000.

[21] R. Narayan, "Tribological Characterization of Biomaterials," 2012.

[22] S. Kucharski and Z. Mróz, "Identification of wear process parameters in reciprocating ball-on-disc tests," *Tribology International,* vol. 44, pp. 154-164, 2011.

[23] H. Meng and K. Ludema, "Wear models and predictive equations: their form and content," *Wear,* vol. 181, pp. 443-457, 1995.

[24] J. Pombo, J. Ambrósio, M. Pereira, R. Lewis, R. Dwyer-Joyce, C. Ariaudo*, et al.*, "A study on wear evaluation of railway

wheels based on multibody dynamics and wear computation," *Multibody System Dynamics,* vol. 24, pp. 347-366, 2010.

[25] T. Pearce and N. Sherratt, "Prediction of wheel profile wear," *Wear,* vol. 144, pp. 343-351, 1991.

[26] X. Shu, M. Dembosky, C. Urban, and N. Wilson, "Rail Wear Simulation and Validation," in *2010 Joint Rail Conference*, 2010, pp. 313-322.

[27] A. Ward, R. Lewis, and R. Dwyer-Joyce, "Incorporating a railway wheel wear model into multi-body simulations of wheelset dynamics," *Tribology Series,* vol. 41, pp. 367-376, 2003.

[28] R. Enblom, "Simulation of Wheel and Rail Profile Evolution: Wear Modelling and Validation," 2004.

[29] J. Pombo, J. Ambrósio, M. Pereira, R. Lewis, R. Dwyer-Joyce, C. Ariaudo*, et al.*, "A railway wheel wear prediction tool based on a multibody software," *Journal of theoretical and applied mechanics,* vol. 48, pp. 751-770, 2010.

[30] A. Bevan, P. Molyneux-Berry, B. Eickhoff, and M. Burstow, "Development and validation of a wheel wear and rolling contact fatigue damage model," *Wear,* vol. 307, pp. 100-111, 2013.

[31] A. Sánchez Arandojo, "On validation of a wheel-rail wear prediction code," 2013.

[32] K. Tanifuji, "A Study on Prediction of Wear Progress of Railway Wheel," Niigata University, Japan. 2015.

[33] A. Shebani, "PREDICTION OF WHEEL AND RAIL WEAR USING ARTIFICIAL NEURAL NETWORKS," PhD, Computing and Engineering, University of Huddersfield UK, 2017.