Addis Ababa University

Addis Ababa Institute of Technology

African Railway Center of Excellence

The Influence of Wheel Flat for Low-Speed train Performance due to Contact Load: A Case Study of Ethio-Djibouti Railway (EDR)

A Research Report Submitted to the School of Graduate Studies of Addis Ababa University in Partial Fulfillment of the Requirements for the Degree of Masters of Science in Railway Engineering (Rolling stock)

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Approval Page

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Yared Wondiye (GSR/9971/13)

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External Examiner	Signature	Date
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ARCE Center Head	Signature	Date

Declaration Page

I hereby declare that the research work entitled "**The Influence of Wheel Flat for Low-Speed train Performance due to Contact Load: A Case Study of Ethio-Djibouti Railway (EDR)**" is my original piece of work and has not been presented for any degree in any other universities.

Yared Wondiye Date

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Abstract

Wheel flats are the most common defect that occurs during train operation. When a train wheel is locked during braking, wheel sliding happens, and as a result, wheel flat rises this wheel flat causes severe impact load on both the vehicle and track components, which leads to excessively damaged railway vehicles and tracks. In this scenario, the Low-speed performance of a train generates higher friction on the wheel/rail contact, which causes wear and defects like wheel flat.

The rigid multi-body system dynamics simulation considered wheel flat defect and track irregularity were established based on SIMPACK software. The present research work is validated based on measurements and relevant research literature. The current work considered the changes in vehicles running speeds from 40km/hr to 100km/hr and wheel flat lengths from 25 mm to 85 mm and studied the dynamic response (vertical force, lateral force & acceleration of the car body), comfort (vertical/lateral), Ride index (vertical/lateral), the influence of speeds.

The results of the analysis showed that the impact load typically rises with running low-speeds and wheel flat lengths, while other parameters, such as vertical acceleration along with its amplitude and power spectrum density rise and reach a maximum value at a specific speed of 70 km/hr, after which it begins to significantly decline.

Finally, the results of impact force for the railway vehicle running at different low speeds and with different wheel flat lengths were analyzed with the warning and alarm limts of impact force that can damage the vehicle and tarck components to classify the running condition as safe, moderate and severe operating condition based on the maximum impact force due to the defects.

Keywords: *Wheel Flat, Rigid Wheelset, Multibody Dynamics, Track Irregularities*

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Nomenclature

Symbols

A- Amplitude

Dxf- Discretization function of specific wheel flat

Lf-wheel flat length

PSD-Power Spectrum Density

Q -Vertical Wheel Force

ΔRf-Change of nominal radius

RI- Ride Index

Wrn-Nominal wheel radius

Abbreviations

CAD- Computer Aid Design

EDR- Ethio-Djibouti Railway

EMU- Electric Motor Unit

FEA-Finite Element Analysis

LTM-Locomotive−Track Coupled Dynamics Model

MBD- Multibody Dynamics

MBS- Multibody Dynamics Simulation

PDL-Plastic Deformation Layer

RCF- Rolling Contact Fatigue

TL-Transition Layer

WEL-White Etching Layer

Chapter 1 - Introduction

1.1 Background

In the history of the railway in Ethiopia, Ethio-Djibouti Railway is the first-meter gauge railway in the Horn of Africa that once connected Addis Ababa to the port city of Djibouti.

Figure 1: Ethio-Djibouti Railway Diesel locomotive with a mixed goods/passenger train on the Holhol viaduct in 1960[1]

It was a 780km meter gauge line built from Addis Ababa to Djibouti by the Ethiopian Emperor Menelik II to facilitate the transport of goods and passengers . The first line was constructed from Djibouti to Diredawa and was open for service in 1901. But the second part extending the line from Diredawa to the capital was not constructed till 1917 due to the bankruptcy of the former railway company. The line was considered the main logistics route and used to give service till the late 20th/early 21st century and closed for service [1].

(a) (b)

Figure 2: a)The Addis Ababa Legehar train station, b) Djibouti City Railway station [1]

Later Ethio-Djibouti Standard Gauge Railway Share Company (or Shortly Ethio-Djibouti Railway (EDR)) was established in April 2017 with new 760km, and 660km lines. In Ethiopia, the standard gauge electrified railway system replaced the former meter gauge railway and started giving service, based on the Bilateral Agreement signed on 16th of December 2016 between the two states, the Federal Democratic Republic of Ethiopia and the Republic of Djibouti. The Shareholders Agreement was subsequently signed on the 11th day of January 2017 among Public Bodies and State Enterprises of the two countries, to be administered pursuant to the commercial laws of Ethiopia [2].

(a) (b)

Figure 3: a) EDR Passenger Train, b) EDR Dire Dawa station[2]

Following the decisions of the Board of Directors, EDR had commenced the Railway Operation and Maintenance activities on January 1, 2018 after a general takeover agreement between the EDR and the respective Railway Companies (ERC and SDCF).

Figure 4: Route of Addis Ababa-Djibouti Railway compared to the Ethio-Djibouti Railway [2]

In the operation of Ethio-Djibouti Railway Trains, wheel flat is one kind of railway train wheelset defect caused by wheel sliding. The presence of imperfections in railway wheels is known to cause severe impact loads on both the vehicle and the track components, and the damage includes hot or broken axles and axle boxes, damaged bearings, cracks penetrating the wheels and rail fracture with the risk of derailment and cracking of concrete sleepers[3]. Besides damage, wheel flats produce excessive vibration and impede operational safety. In addition to safety and economic considerations, these defects also reduce passenger comfort and significantly increase annoying noise. The safe, cost-effective, and environment-friendly operations of railways thus necessitate continuously[4].

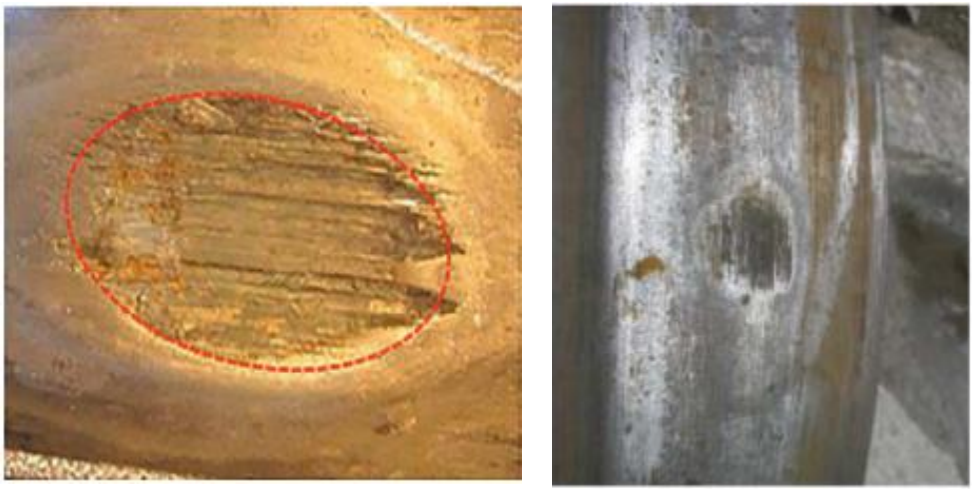


Figure 5: Wheel Flat [5, 6]

Wheel flats generally arise when a train wheel is locked during braking due to poorly adjusted or defective brake systems or a braking force that exceeds the available wheel–rail friction force temporarily (adhesive force between wheel and rail). A second reason for the generation of wheel flats is a local wheel– rail adhesion force reduction of an operating train wheel, leading to slip. The latter reduction can occur due to snow on the rails based on geographical events, lubrication, or the presence of leaves in autumn[3]. When wheel flat damage happens on wheels, the instantaneous center of rotation on the wheel is changed. Every time the flat damage contacts the rail, there is instantaneously vertical impact velocity towards the rail, which may cause a series of vibration and impacts. The Ethiopia-Djibouti Railway's low speed trains, among others, had certain wheel defects, including a wheel flat.

Figure 6: Defect occurred on EDR Train wheels with a small wheel flat

1.2 Statement of the Problem

In studying railway engineering, wheel/rail interaction is critical because it considers the safety, reliability, performance, comfort, and ride indicators of railway vehicle dynamics systems. This dynamic system behavior is affected by the defects on the wheelset produced by wheel/rail interaction. The leading causes of these defects are heat generation from sliding, wear, flow, improper steering bogies, and excessive breaking or conditions that reduce friction between the wheels and tracks, such as diesel spills, leaves on the line, chemicals, or stormy weather conditions. Wheel flat is one type of railway train wheelset defect. A train wheel is locked during braking due to defective brake systems or a braking force that exceeds the available wheel/rail friction force (adhesive force between wheel and rail). Wheel/rail adhesion force reduction of an operating train wheel, wheel sliding happens and causes heat generation that will affect the underlying material. As a result, wheel flat raises causes severe impact load on both the vehicle and track components, leading to excessively damaging railway vehicles and tracks such as damaging axles, axle boxes, bearings, cracks that penetrate the wheels, and railroad breaks may derail.

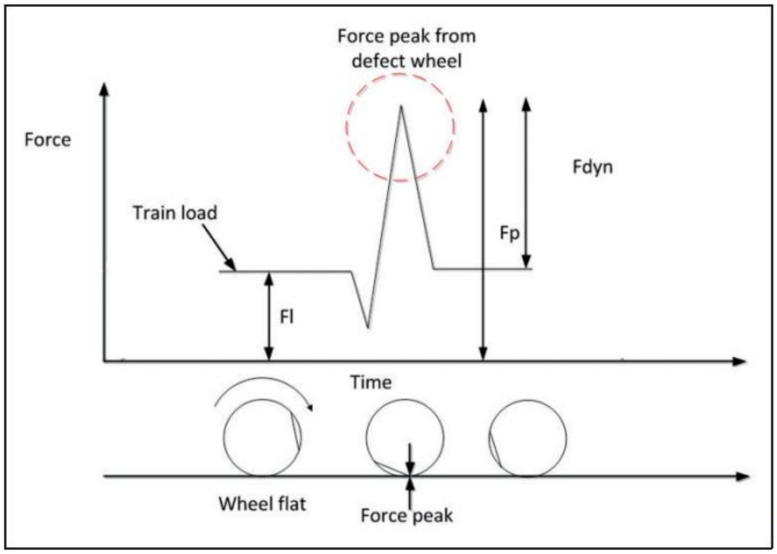
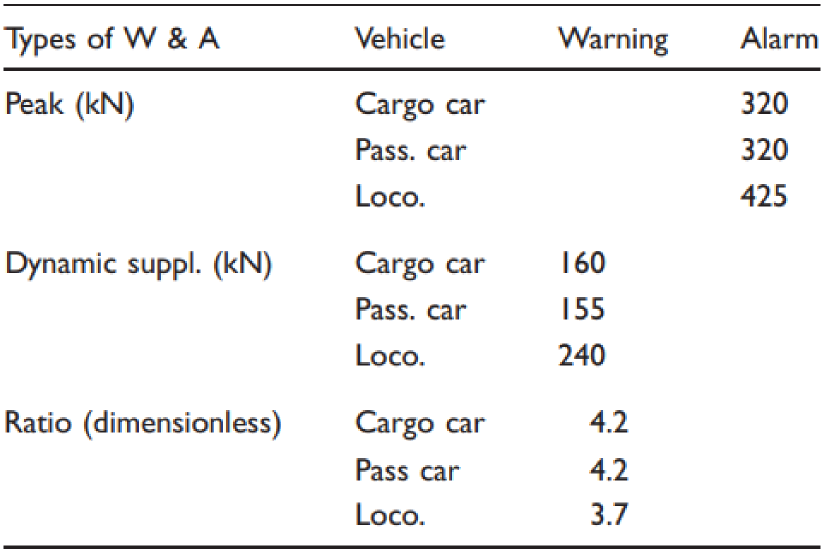


Figure 7: Hypothetical description of the force load of a wheel defect [7]

Many researchers have concentrated on impact forces caused by wheel/rail defects for high-speed train performance. However, the low-speed performance of a train also generates higher friction on the wheel/rail contact, which causes wear and imperfections like wheel flat. According to Matthias Asplund[7],the Wheel defect impact load warning limit is 155KN and alarm limit is 320KN for Passenger vehicle types as shown on table 1.

Table 1: Wheel defect detector warning (W) and alarm (A) limits for different vehicle types[7]



Types of W & A	Vehicle	Warning	Alarm
Peak (kN)	Cargo car		320
	Pass. car		320
	Loco.		425
Dynamic suppl. (kN)	Cargo car	160	
	Pass. car	155	
	Loco.	240	
Ratio (dimensionless)	Cargo car	4.2	
	Pass car	4.2	
	Loco.	3.7	

Based on related study made on the impact load due to wheel flat at low speed operationg condition ,the wheel rail impact force is higher than warning and alarm limits given by Matthias Asplund[7].

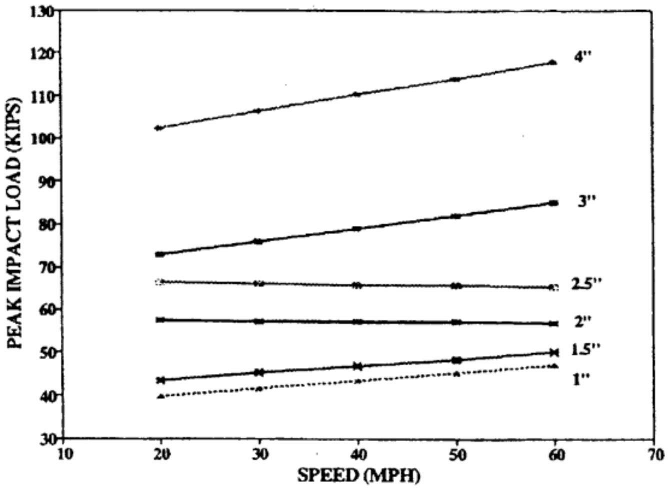


Figure 8: Expermental measurements of impact loads from wheelflat versus train speed at different size of the wheelflat[8].1kip=4.45kN,1mile/h=1.609km/h and 1inch=25.4mm

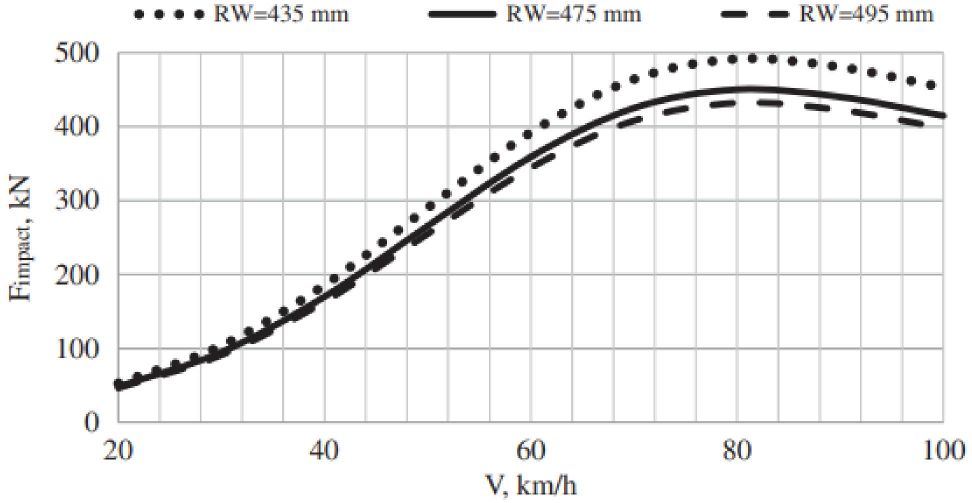


Figure 9: Dependency of impact force on railway vehicle speed and radiuses of wheel with flat (L = 100 mm)[9]

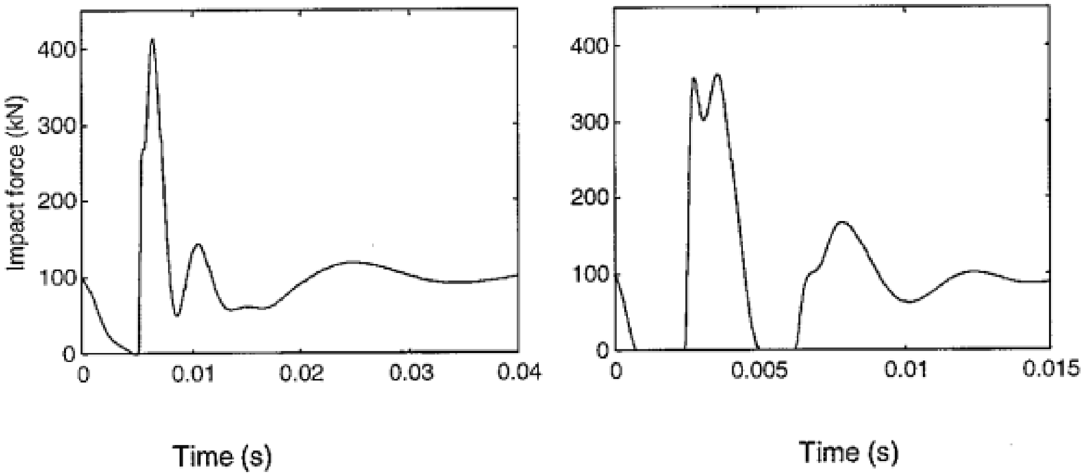


Figure 10:Wheel/rail interaction due to newly formed wheel flat with depth=2mm & Length=86mm a) at train speed 30km/hr and b) at 80km/hr[10]

The above results of related literatures shows that at low speed running condition of a train, the presence of wheel flat will cause additional impact forces higher than the warning and alarm limits of impact load at the wheel-rail interaction which is likely to cause a more rapid fatigue failure of locomotive and infrastructure components ,therefore it is necessary to determine the dynamic effects of the wheel flat on the railway vehicle system running at low speed so as to allow efficient monitoring and maintenance. As a result, there is a need to investigate the impact of wheel flat on low-speed train performance, such as Ethio-Djibouti Railway (EDR) trains, due to contac t load in terms of impact force, vertical acceleration, along with its amplitude and power spectrum density (PSD), and comfort level (ride index), to reduce the consequences as much as possible in order to minimize the maintenance cost of the vehicles and their components.

1.3 Research Question

- What are the main causes of wheel flat for the low-speed train of EDR?
- What is the relation between low-speed performance and wheel flat?
- At which low-speed range of the EDR Train impact load is severe enough to cause the wheel to be flat?
- What is the impact of wheel flat for low-speed train performance due to contact load?
- What parameters did affect the wheel flat that occurred on EDR Trains?
- What countermeasures do we have to take to reduce wheel flat occurring on the EDR Train wheels?

1.4 Objective

The main objective of this Thesis work is to study the influence of wheel flat on the train Performances under low-speed as a main factor using SIMPACK.

Specific Objectives

The specific objectives are:-

- ✓ Analyzing the vehicle and track related factors that influence wheel flat and determine which ones are dominant.
- ✓ Determine the effect of low running speed, wheel flat length and track irregularities on the impacts of wheel flat.
- ✓ Demonstrate the effect of wheel flat due to low running speed,wheel flat length and track irregularity on vehicle dynamic behavior.
- ✓ To study the influence of wheel flat on the dynamic response, comfort, Ride index, influence of speeds & safety for low-speed trains of Ethio-Djibouti Railway.
- ✓ To study the Dynamic Behaviors, simulate and analyze the model through different low-speed ranges and wheel flat lengths with Multibody Dynamics Simulation (MBS).

1.5 Significance of the Study

Significance of the study for the case study Trains of Ethio-Djibouti Railway S.C (EDR)

- In terms of cost and maintenance**: -** Since wheel flats cause damage to the vehicle and track components, the maintenance cost of trains of Ethio-Djibouti Railway is high. This study helps to identify the causes of these wheel flat influences and state the countermeasures that need to be taken to reduce those damages. This helps to increase the durability of the components to reduce maintenance costs.
- The performance may be affected in terms of reliability and performance due to the repeated wheel flat occurrence on the wheelsets and resulting from damages to the vehicle and track components of EDR trains. Additionally, the present study will help solve the problems by identifying the causes and influences and stating the countermeasures that need to be taken to improve or sustain the performance and reliability of EDR.

Research output for different world rail transports

Studying the dynamic behavior of wheel flat for low-speed train performance helps to:-

- ✓ Show the effect wheel flat at low speed running conditions of the vehicles
- ✓ Reduce the risk of damage to infrastructure caused by wheel flat defects
- ✓ Minimize hunting/maintaining good vehicle stability
- ✓ Minimize wheel/rail contact stress to prevent rolling contact fatigue in wheel and rails

1.6 Scope and Limitation of the research

A software simulation using actual EDR passenger coach specifications and tracks was carried out to explore the impact of wheel flat on the operation of EDR trains with different running speeds and wheel flat lengths. Data was acquired about certain situations in which wheels would flat, harming and inconveniencing passengers. As several aspects may be taken into account to gain a complete picture of the factual scenario, the research's findings are restricted to the impact of the above parameters on Wheel Vertical Force, Acceleration, Ride Index, Amplitude, and Power Spectrum Density(PSD). Another limitation on the scope of the investigation is the absence of complete Parameters and wheel flat data for EDR passenger Coaches.

1.7 Organization of the Thesis

The organization of this Thesis work given below:-

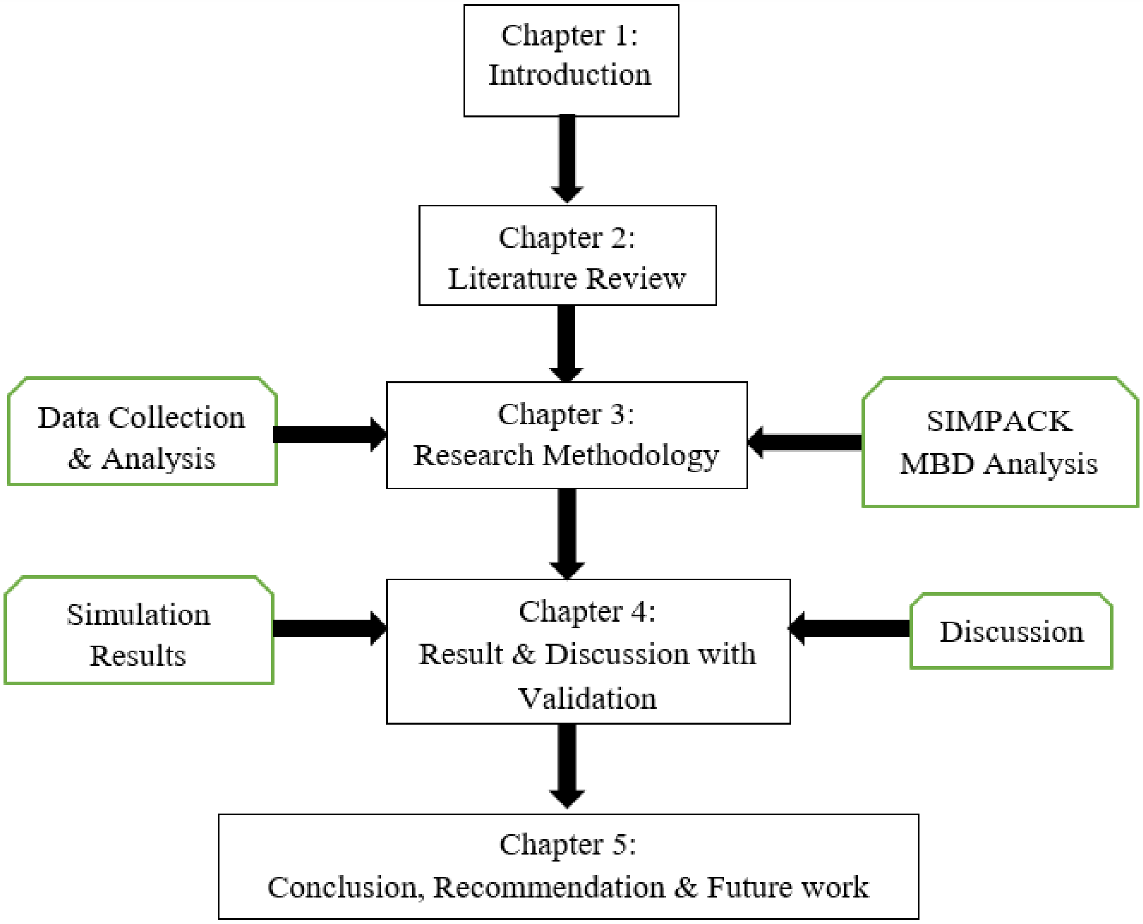


Figure 11: Organization Flow Chart

Chapter 2 - Literature Review

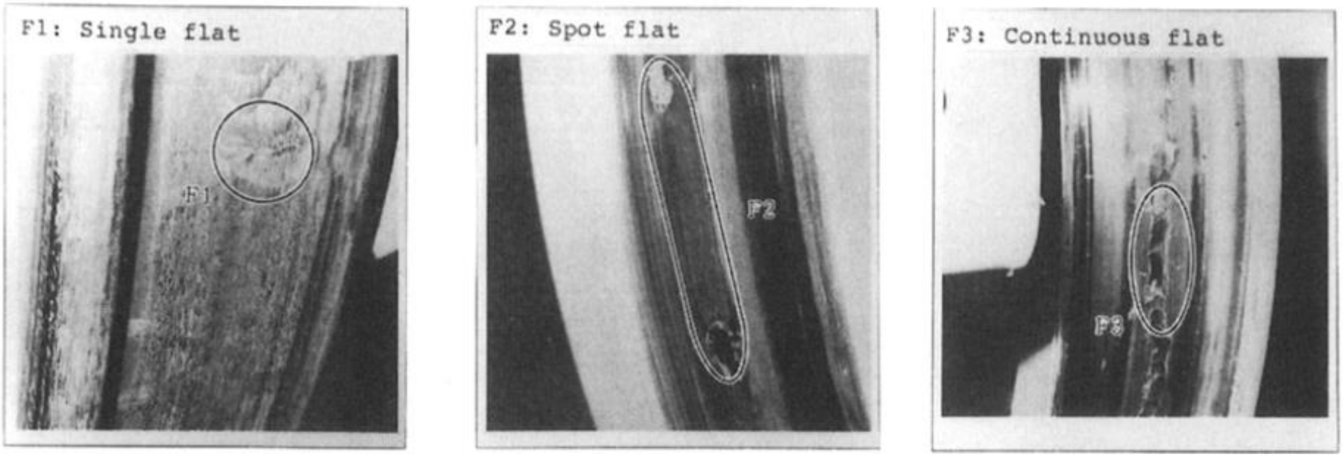
2.1 Introduction

In the operation of railway line,wheel tread imperfection occurs after a service life of the dynamic vehicles. This defects have a detrimental influence on both track and vehicle components such as sleepers,rails, wheelsets and bearings. The disastrous eschede accident in Germany in june 1998 may have started with a fatigue crack in the wheel rim caused by the fluctuating contact force on non-round wheel tread or wheel-out of roundness(OOR)[8].

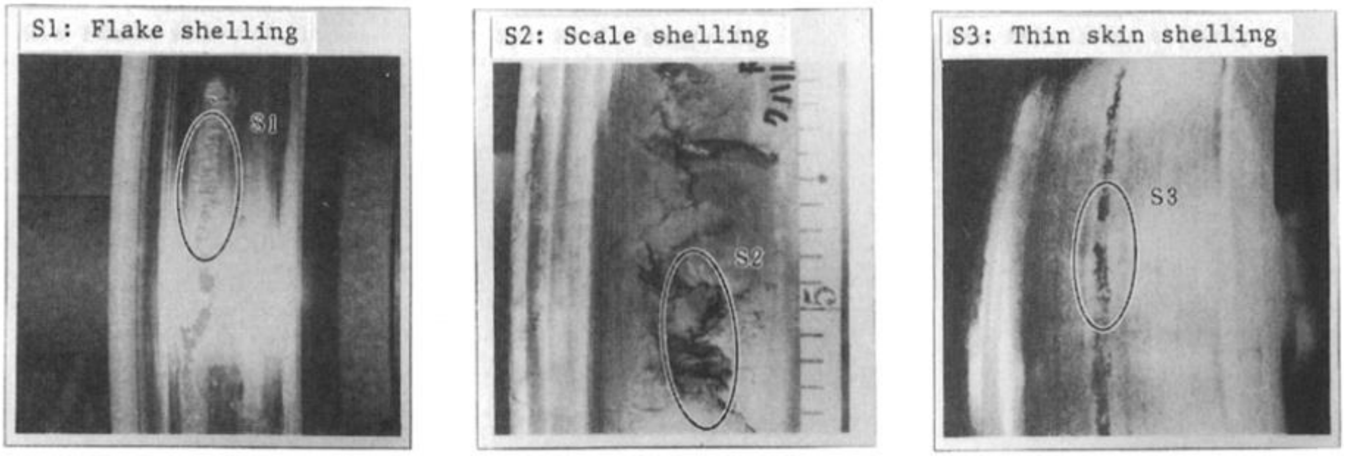
According to J. C. O. Nielsen[8], classification of different types of defects on railway wheel tread given below:-

- **Eccentricity:** caused by misalignment in the fixation of the wheel during profiling or reprofiling, and it is present to some extent on all railway wheels
- **Discrete defect:** is adevation of the wheel radius that is present over a small part of the tread may be caused by wheelflat or by inhomogeneous material properties
- **Periodic non-roundness:** This type of OOR has a periodic irregularity around the wheel circumference superimposed on the constant wheel radius. The wavelength of the irregularity ranges from 14 cm to approximately one wheel circumference, while the amplitude is of the order of 1 mm. This defect has been detected only on disc-braked wheelsets.
- **Non-periodic (stochastic) non-roundness:** This type of OOR may be caused by unbalances in the wheelset or by inhomogeneous material properties of the wheel. As for periodic non-roundness, this defect has been observed only on disc-braked wheelsets.
- **Corrugation:** This defect appears on wheel treads that are block braked. The dominating circumferential wavelength of this type of OOR is 3–6 cm, while the amplitude is smaller than 10 μm. It is noted that corrugation is a main source of rolling noise.

- **Roughness :** The circumferential wavelength of this defect is in the order of magnitude of 1 mm, while the amplitude is of the order of 10 μm.
- **Flats :** This type of defect is due to unintentional sliding (without rolling) of the wheel on the rail. The primary cause is that the braking force is too high in relation to the available wheel/rail friction. The reason for this may be that the brakes are poorly adjusted, frozen or defective. Another reason may be that there are regions where wheel/rail friction incidentally and locally becomes low.
- **Spalling or Thermal Cracks:** Spalling is the term used for the rolling contact fatigue phenomenon occurring when surface cracks of thermal origin meet, resulting in part of the wheel coming away from the wheel tread. The thermal cracks may arise in the hard and brittle martensite that is developed owing to heating and rapid cooling of the wheel tread during and after block braking.
- **Shelling :** Shelling is a term normally used for all types of subsurface induced cracks. It is manifested by loss of flakes of material from the wheel tread. Excessive vertical wheel/rail contact forces with respect to the diameter of the wheel is the primary cause for this particular form of rolling contact fatigue.



a) Flat



b) Shelling

c) Termal Crack

Figure 12: Classification of wheel damage[11]

2.2 Wheel flat

Wheel flat is a major type of wheel tread defect occurred after a service life of railway vehicles.When the surface of rails is wet on a rainy day or a frosty morning, wheels skid on the rails and wheel tread flats are generated instantly upon braking. The existence of defects especially the most common wheel flat contributes the most to the abnormal changes in vertical force, that result in abnormal vibrations between in vehicle-track system, the vibration due to wheel flat wheel spread from the contact point between wheel and rail upward to bogie and car body, downward to ballasts and subgrade [12].Wheel flats cause passenger discomfort through vibration and noise and inflict mechanical damage to the vehicle and track components such as bearings and axles if they are not removed.

According to N. Kumagai[11], Flats are classified into three modes as shown in Fig. 12(a).

- Single flat: A single flat is an oval-shaped area of damage caused by locking of an axle in car running and is often observed with trailer axles.
- Spot flat: A spot flat is a set of small single flats.
- Continuous flat: A continuous flat, which is long and slender, is caused when an axle skids on the rails without wheel locking. This flat is likely to occur with motor car axles in particular. Plastic flow of wheel material is often observed.

Wheel flats, causing severe repeated high-frequency impact loads, The most severe type of wheel defect is a newly developed wheel flat with sharp edges. Older wheel flats with rounded edges may also damage sleepers and ballast [8].

2.3 Stability and Safety

2.3.1 Nadal’s Formula for Safety Criteria

The derailment of wheels from the rail is one of the devastating failures that could occur in a railway system. Derailment is a process by which the lateral force imposed on the wheel pushes it against the rail at the contact patch raising the wheel way above the rail gauge resulting in wheel climbing and if further kept results in derailment. In order to avoid this phenomenon, safety criteria are device to quantify it by different publications. These include Weinstock axle-sum L/V criteria, High speed passenger limit criteria (US), L/V time duration criterion (Japan) and Nadal’s single-wheel L/V limit criterion [13]. From the above, Nadal and Weinstock criteria are related to L/V ration limits while the rest are related to the time and distance exceeding limits of L/V. The Nadal’s safety criterion is proposed for French railways based on a subsequent flange contact due to excess lateral force and it is expressed as follows.

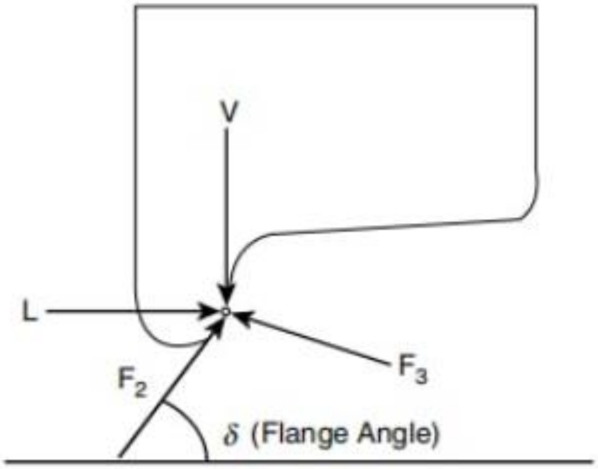


Figure 13: Vertical and lateral force application at contact patch[13]

$$\frac{L}{V} = \frac{tan\ \delta - \mu}{1 + \mu tan\delta} \qquad \text{Eq 1}$$

Where: L = Lateral force, V = Vertical force, μ = friction coefficient and δ = flange angle

According to the safety criteria, the value L/V shall not exceed value of 0.8 for avoiding wheel climbing during operation of the trains.

2.3.2 Comfort

For general comfort conditions according to the UIC approach takes the following expression for ride quality computation[13]:

$$N\text{MV}=\sqrt[6]{((\ \alpha\text{xp}95)^2 + (\alpha\text{yp}95)^2 + (\alpha\text{zp}95)^2)} \qquad \text{Eq 2}$$

Where: NMV = Ride Quality, α_{xp} = acceleration in longitudinal direction, α_{yp} = acceleration in lateral direction, α_{zp} = acceleration in the vertical direction.

The maximum peak acceleration that could be achieved in all of the directions is estimated as 0.3g = 2.943m/s^2 by taking 30% adhesion at most [13]. Further, for N<1= very comfortable,1<N<2 = comfortable , 2<N<4= medium comfort, 4<N<5=Uncomfortable and N>5 Very uncomfortable conditions hold true. These values are described as ride index in the analysis following and the best comfort condition to be below 1.6.

2.4 Related Published literatures

In here related researchs done around the topic reviews and most of the researches constitute the following four main components of the overall system modeling, i.e., Vehicle Dynamic Model, Wheel-rail interaction model, wheel flat model and finally a validation system for confirmation of the results obtained.

J. Zhu [4] studied Impact load due to railway wheels with multiple flats and suggests that the magnitude of impact force attributed to the second flat entering the contact region is strongly affected by the responses due to the preceding flat, depending upon the flat geometry, relative co-ordinates of the flats and the operating speed. And also the length of a flat alone, which is commonly regarded as wheel removal criteria, may not be adequate when multiple flats are present.

An adaptive contact model, a two-dimensional roll-plane vehicle model, a three-dimensional track model and Hertzian contact model were developed to investigate the wheel–rail impact load due to multiple flats. Further study is recommended to establish clear guidelines that may be used by industry for maintenance and removal of wheels due to multiple flats as a future work.

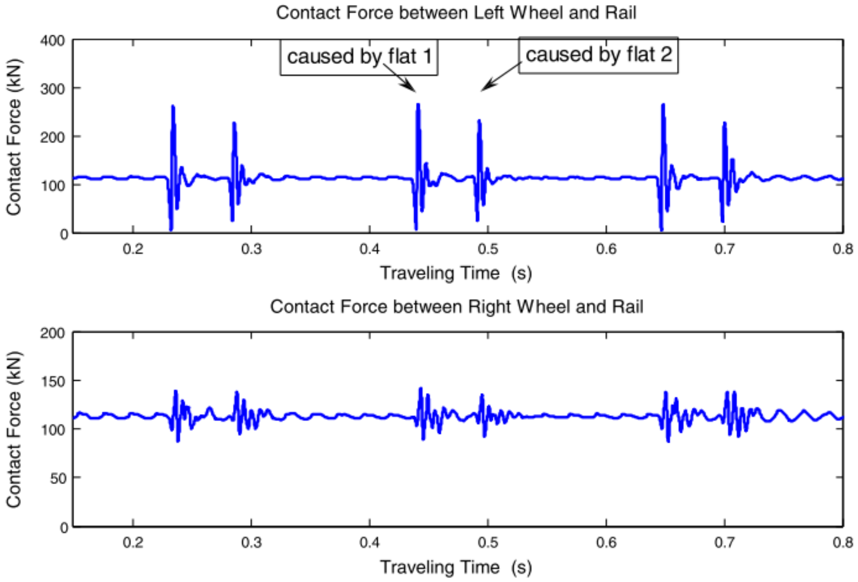


Figure 14: Time history of wheel rail contact force due to two flats 90◦ apart[4]

A. Momhur [5] shows that the rigid wheel flat has the highest vertical wheel impact load and is more significant than the flexible wheel flat force and suggest that the wheelset flexibility can significantly improve vertical acceleration comparably to the rigid wheel flats.The impact evaluation induced by the wheel flat was proposed via the finite element analysis (FEA) software package ANSYS, integrated into a multibody dynamics model of a typical Chinese high-speed train, CRH2A (EMU) through SIMPACK and the irregularity track line has developed and depends on the selected simulation data points and a flexible and rigid wheel flat were introduced in multibody dynamics (MBS) to obtain vertical impact loads and statistical methods to evaluate dynamic performance and vehicle dynamic safety. They put a future work which is vehicle performance, safety, comfort, and stability can be evaluated according to the given statistical methods.

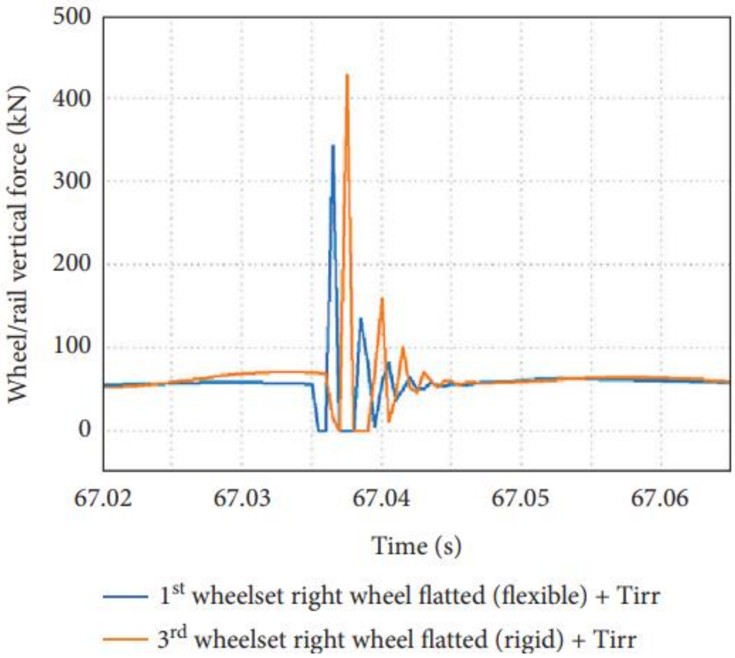


Figure 15: Time history of wheel/rail vertical impact force flat length of 50 mm with track irregularity (Tirr)[5]

R. Zunsong [6] shows that the width, the length of the wheel flat and the width/length ratio have a great influence on the wheel/rail impact dynamics. The wheel/rail impact dynamics of the flat with large width is more severe than with small width as the flat length is fixed, it suggests that all of the flat length, width and width/length ratio of the wheel flat should be taken in to account to make the safety criteria. A three-dimensional wheel flat model considering the length, width and depth of the flat spot is established and a high-speed vehicle–rail coupling system dynamics model is developed to study the effect of the wheel flat on the wheel/rail impact dynamics using a time integration method. As a research gap to validate the simulation results field test didn’t make because of the operation safety and the cost, for the future work more experimental test is required to validate the simulation result of this paper.

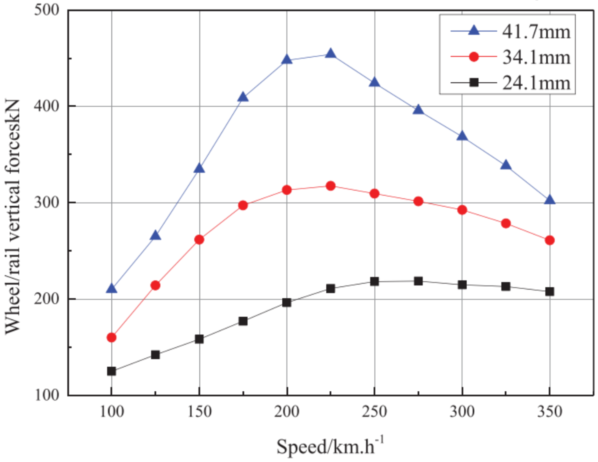
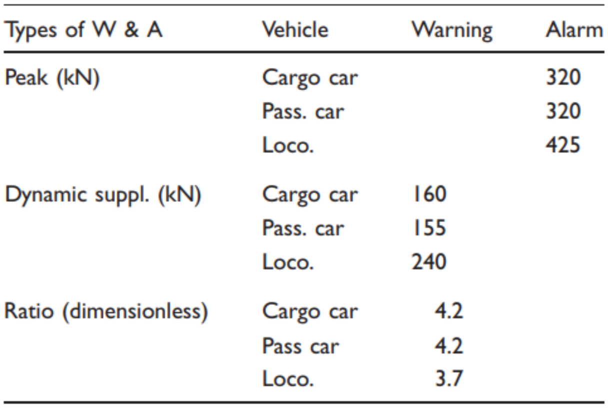


Figure 16: The effect of the flat width on the wheel/rail dynamic impact (Flat length l = 50 mm)[6]

Matthias Asplund [7]study railway wheel profile parameters used as indicators of an increased risk of wheel defect like wheel flat to inspect rolling stock so as to prevent damage to the track due to faulty wheels, infrastructure managers normally install wayside monitoring systems such as wheel defect detector (WDD) and wheel profile measurement system (WPMS) along the track. In this paper, wheel profile parameters measured by a wayside wheel profile measurement system, installed along the Swedish Iron Ore Line, are examined and related to warning and alarm indications from a wheel defect detector installed on the same line. The study shows that an increased wheel defect, detectable by changes in the wheel profile parameters, could be used to reduce the risk of capacity-limiting wheel defect failure events and their reactive measures , the percentage of wheels with warnings/alarms increases with an increase in flange height and the approximate length of a flat that would generate an alarm is around 60 mm [7].



Types of W & A	Vehicle	Warning	Alarm
Peak (kN)	Cargo car		320
	Pass. car		320
	Loco.		425
Dynamic suppl. (kN)	Cargo car	160	
	Pass. car	155	
	Loco.	240	
Ratio (dimensionless)	Cargo car	4.2	
	Pass car	4.2	
	Loco.	3.7	

Figure 17: WDD installed along the Iron Ore Line in Sweden.[7]

J. C. O. Nielsen [8] discusses why out-of-round railway wheels are developed and on the damage they cause to track and vehicle components. In this survey experimental detection of impact load using strain gauges or accelerometers such as WILD (Wheel Impact Load Detector) ,mathematical modeling and Numerical simulation of the influence of out of round wheels were reviwed and suggests that, in order to minimize costs for repair and maintenance and to meet noise legislation, there is a large economic incentive for detecting and replacing non-round wheels in time. Different creteria for the removal of out of round wheel given by [8]:

- For North American conditions, wheels should be removed from service when they cause impact loads greater than 85 kips (378 kN).
- In Sweden, the criteria for wheel repair are: If the length of the wheelflat defect is 40–60 mm with the measured wheel impact loads of 290kN , or if there exists a material build-up but with a height smaller than 1 mm, the train has to go to the nearest workshop for repair. On such an occasion and at temperatures below-10 °C, the train speed must not be higher than 10 km/h. At higher temperatures, there are no restrictions other than that the speed interval 15–45 km/h should be avoided since the risk of damaging the rails is largest at these speeds. If the length of the wheelflat damage is larger than 60 mm with the measured wheel impact loads of 320kN, or if the height of a material build-up is larger than 1 mm, the train must go to the nearest manned station at a speed not higher than 10 km/h.

Marijonas Bogdevicius [9] demonstrates the influence of wheel with flat geometrical parameters, speed of vehicle to maximum contact force and its distribution in the contact zone. The result shows that that the impact force increases fast, when the flat depth is 2.53 mm and the wheel speed is rising from 0 to 80 km/h, but when the speed is above 80 km/h, the raise of the impact force is slower. This tendency of impact force changing is the same at different flat lengths.

Vertical contact load determination method (CLDM) were developed for the determination of Maximum impact force F_{impact} dependencies on the most affected parameters of the system, then compared with experimental tests.

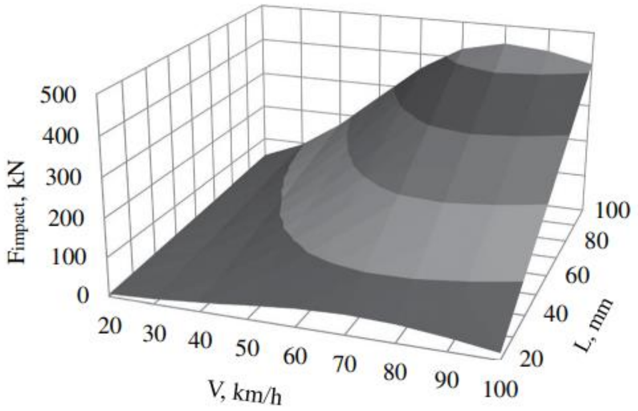


Figure 18: The dependency of impact force Fimpact on the speed of railway vehicle V and the length of the wheel flat.[9]

T.X. Wu [10] explores noise generation and impact force due to wheel flats, The noise level due to wheel flat excitation is found to increase with the train speed V at a rate of about 20 $\log_{10}V$ whereas rolling noise due to roughness excitation generally increases at about 30 $\log_{10}V$ and the impact force caused by wheel flats is related to both the shape of the wheel flat and the train speeds. In order to calculate the wheel/track interaction force, a simplifed track model is developed and combined with the wheel through a non-linear Hertzian contact stiffness. From the combined system of the wheel, contact stiffness and track, dynamic interactions between the wheel and rail are simulated in the time domain. The results are then analyzed in the frequency domain and the results are compared for different types of wheel flat and different train speeds.

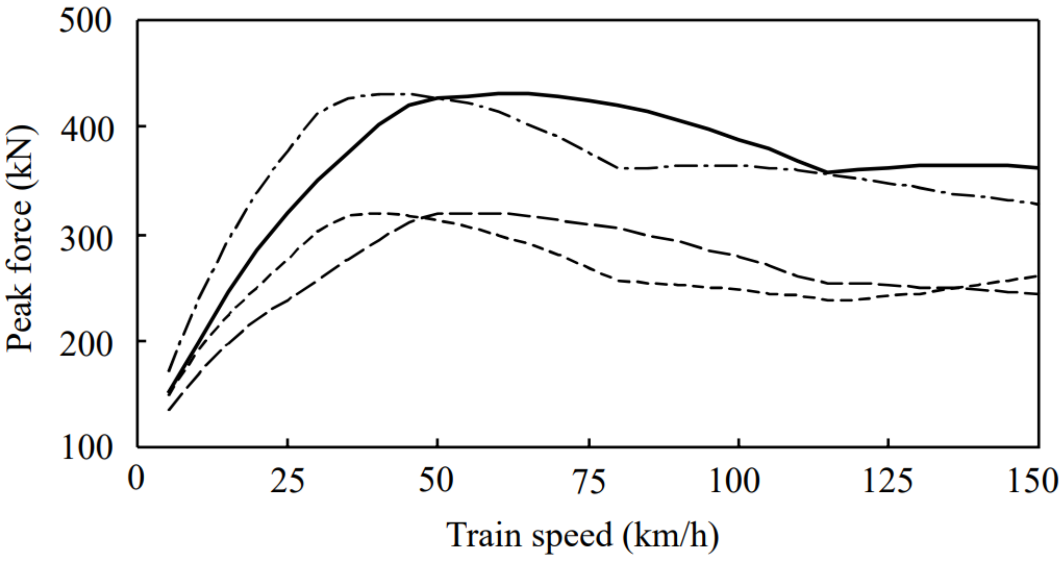


Figure 19: Peak impact force caused by different wheel flats:___, due to 121 mm rounded flat; - - -, 86 mm rounded flat; -.-.-.-, 121 mm newly formed flat; ….. , 86 mm newly formed flat[10]

B. Guo [14] investigates the effect of the wheel flat on the service life of the motor bearings and results that the periodic impact forces and larger mesh forces caused by the wheel flat will reduce the fatigue life of the motor bearings, especially when the flat length is larger than 30 mm. A fatigue life prediction method of the traction motor bearing in the environmental vibration of a locomotive is proposed via incorporating the time−varying displacement excitation induced by the wheel flat into the locomotive−track coupled dynamics model (LTM) and as research gab the fatigue lives of axle box bearings of the locomotive or wagon can also be investigated by using the above method,

R. V. Dukkipati [15] studied Impact Loads due to Wheel Flats and Shells and suggests that the shape and size of flat or shell, axle load, vehicle speed & rail-pad stiffness mainly affect the impact loads. A Finite Element (FE) model of vehicle-track system is employed and validated against the available experimental data from British Rail and CP Rail. The validated model is then used to carry out an extensive parametric study to identify all possible factors that may affect the impact load and also to examine the interaction between two wheels due to wheel tread defects. Improvements on the automatic detectors of wheel flat to increase their reliability is the future work of the article.

V.Belotti [16] present a diagnostic tool based on the wavelet transform and shows that the dependence of the impact force from the wheel-flat depth is not linear, this high non- linearity between the impact force and the wheel-flat length it is difficult to quantify the damage entity and some constraints should be applied to diagnostic quantification procedure such as

- ✓ Softly damaged:- The wheel-flat length is less than 40 mm, and then the coach could stay on duty
- ✓ Heavily damaged:- The wheel-flat length is 40 mm or more, and then the coach should go to maintenance.

To detect the impact force caused by wheel flat, a series of accelerometers were installed on the rail, and the signals were analyzed based on the wavelet property of variable time–frequency resolution. For the experimental tests, the Italian Railway Workshop of Florence artificially produced the flats, which could be considered as new wheel-flat defects: they have sharp edges on the corner with train composition of one electric locomotive for passenger transport, without wheel defects, three testing passenger car cabs with defected wheels, 30mm wheel flat, 45mm wheel flat and 15mm wheel flat respectively and one ends cab without wheel defects,

Y. Chen [17] Describes that the microstructure of wheel flat zone is composed of white etching layer (WEL), transition layer (TL), plastic deformation layer (PDL).Meanwhile, the sliding values increases with the braking speed increasing, so the mechanical action caused by wheel sliding on the rail surface increases and the temperature caused by friction heat becomes higher. They lead the damage of wheel flat zone to become more severe, the more serious damage makes the impact greater, with the braking speed or braking time increasing, the fatigue damage of wheel flat zone worsen and the thickness of WEL increases, which brings an increase of fatigue crack length and propagation angle.

Different wheel flats were generated under different braking conditions through a JD-1 wheel/rail simulation facility manufactured by Southwest Jiaotong University(Japan). Then, rolling contact fatigue (RCF) tests with different wheel flats were carried out to explore the influence of wheel flat on RCF characteristics of wheel materials using various microscopic examinations,

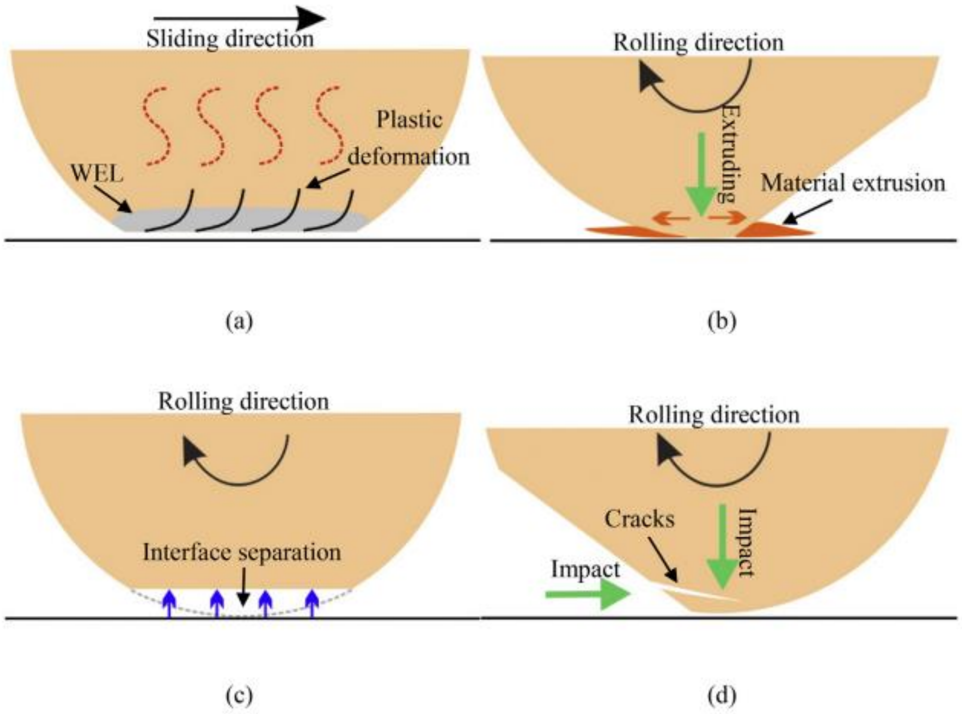


Figure 20: Schematic representation of wheel flat damages, (a) wheel flat formation process; (b) the front of wheel flat contacting with rail roller; (c) wheels separating from rail roller; (d) the back of wheel flat contacting with rail roller.[17]

X. Wei [18] studied a wheel-flat detection method based on vehicle system acceleration measurement and suggests that installing the accelerationsensor on the axle, bogie and car-body can detect the flat fault. Considering actual operation, installing the acceleration sensor at the four corners of the bogie is the most appropriate. Mounting the acceleration at the axle could cause large changes to the whole vehicle system, which could reduce the life of the vehicle system and should be avoided. According to X. Wei [18], if the acceleration sensors are installed on the car-body, they cannot detect the flat fault very well, due to the influence of suspension system.

A simulation model with acceleration sensors was made up using SIMPACK, and the data acquired in the post-processing section of the SIMPACK will be analyzed using MATLAB. The Fourier Transform is applied to analyze the data obtained from the simulation model, and the analysis consists of two sections, namely, time domain analysis and frequency domain analysis. Each of the analyses includes waveform analysis and parameter analysis. L. Jing [19] investigate the wheel-rail impact responses dut to wheel flat and shows that the wheel-rail impact responses first increases and then decreases with the train speed; however, they are increased with the increasing axle load. With the increase of flat length, the maximum impact force, von Mises equivalent stresses and XY shear stresses increase, and the maximum equivalent plastic strains decrease correspondingly. The finite element method (FEM)-based wheel-rail rolling contact model with a new wheel flat was built to investigate the wheel-rail impact responses, and two basic dynamic effects (i.e., inertia effect and strain-rate effect) and temperature effect during the wheel-rail sliding process were considered.

Table 2: Summary of related literatures

No	Title	Autors	Methods	Basic Findings	Year	Ref. No.
1	Impact load due to railway wheels with multiple flats predicted using an adaptive contact model	J. Zhu, A. Ahmed, S. Rakheja, and Y. Hu	Hertzian Theory and adaptive contact model	The magnitude of impact force attributed to the second flat entering the contact region is strongly affected by the responses due to the preceding flat	2009	[4]
2	Flexible-Rigid Wheel set Introduced Dynamic Effects due to Wheel Tread Flat	A. Momhur, Y. Zhao, L. Quan, S. Yazhou, & X. Zou	Finite element analysis (FEA) software package ANSYS, integrated into a MBD through SIMPACK	Rigid wheel flat has the highest vertical wheel impact load and is more significant than the Flexible wheel flat force & wheelset flexibility can significantly improve vertical acceleration	2021	[5]
3	An investigation on wheel/rail impact dynamics with a three-dimensional flat model	R. Zunsong	Time integration method of the models	The width, the length of the wheel flat and the width/length ratio have a great influence on the wheel/rail impact dynamics	2019	[6]
4	A study of railway wheel profile parameters used as indicators of an increased risk of wheel defects	M. Asplund, M. Palo, S. Famurewa & M. Rantatalo	wheel defect detector (WDD) and wheel profile measurement system (WPMS)	Wheels with warnings/alarms increases with an increase in flange height and the approximate length of a flat that would generate an alarm is around 60 mm	2014	[7]
5	An analytical mathematical method for calculation of the dynamic wheel–rail impact force caused by wheel flat	M. Bogdevicius, R.Zygiene, G.Bureika & S. Dailydka	Vertical contact load determination method (CLDM) with experimental tests.	The impact force increases fast for speed is rising from 0 to 80 km/h, but when the speed is above 80 km/h, it is slower at flat depth is 2.53 mm.	2016	[9]

6	A Hybrid Model for Wheel/Track Dynamic Interaction and Noise Generation Due to Wheel Flats	T.X. Wu and D.J. Thompson	Non-linear Hertzian contact stiffness model, simulated in the time domain.	The noise level due to wheel flat increase with the train speed V at a rate of $20 \log_{10}V$ and the impact force related to both the shape of the wheel flat and the train speeds	2001	[10]
7	Dynamic Influence of Wheel Flat on Fatigue Life of the Traction Motor Bearing in Vibration Environment of a Locomotive	B. Guo, Z. Luo, B. Zhang, Y. Liu, and Z. Chen	Time−varying displacement excitation based on L−P theory and ISO 281, combined with the Miner linear damage theory	Periodic impact forces and larger mesh forces caused by the wheel flat will reduce the fatigue life of the motor bearings, especially when the flat length is larger than 30 mm.	2021	[14]
8	Impact Loads due to Wheel Flats and Shells	R. V. Dukkipati and R. Dong	Finite Element (FE) model developed validated against the available experimental data from British Rail and CP Rail	The shape and size of flat or shell, axle load, vehicle speed & rail-pad stiffness mainly affect the impact loads	1999	[15]
9	The influence of wheel flats formed from different braking conditions on rolling contact fatigue of railway wheel.	Chen, Y., et al.	JD-1 wheel/rail simulation to explore the influence of wheel flat on RCF characteristics of wheel materials using various microscopic examinations	More severe wheel flat zone makes the impact greater which brings an increase of fatigue crack length and propagation angle.	2018	[17]
10	Wheel-rail impact by a wheel flat	Jing, L.	The finite element method (FEM)-based wheel-rail rolling contact model with a fresh wheel flat	The wheel-rail impact responses first increases and then decreases with the train speed; however, they are increased with the increasing axle load.	2018	[19]

2.5 Research Gap

In general, even though most of the research papers study the effect of impact load due to wheel flat, which influences the vehicle /track components by considering mainly high-speed trains given by A. Momhur and R. Zunsong [5, 6]. But result of the study by J. C. O. Nielsen, M. Bogdevicius T.X. Wu [8-10] shows that at **low speed running** condition of a train, the presence of wheel flat will cause additional impact forces higher than the warning and alarm limits of impact load given by M. Asplund [7] at the wheel-rail interaction which is likely to cause a more rapid fatigue failure of locomotive and infrastructure components. The above-reviewed literature [8-10] works on the effect of wheel flat based on flexible wheelset for modeling and uses Finite Element (FEM) method and Time-Domain Method for analysis and simulation but not including track irregularity.

However, as a research gap it is necessary to determine the dynamic effects of the wheel flat on the railway vehicle system running at low speed so as to allow efficient monitoring and maintenance. It is also imperative that EDR trains are grouped under low-speed division according to[20].The current research work mainly inclined their investigation to wards high-speed trains. Moreover, the present thesis considers the dynamic behaviour of the low speed of the Ethio-Djibouti line integrated with wheel flat damage based on riged wheelset for modeling and uses Simpack Multibody Dynamics method for analysis and also considering track irregularity.

Chapter 3 - Research Methodology

The research methodology given below:-

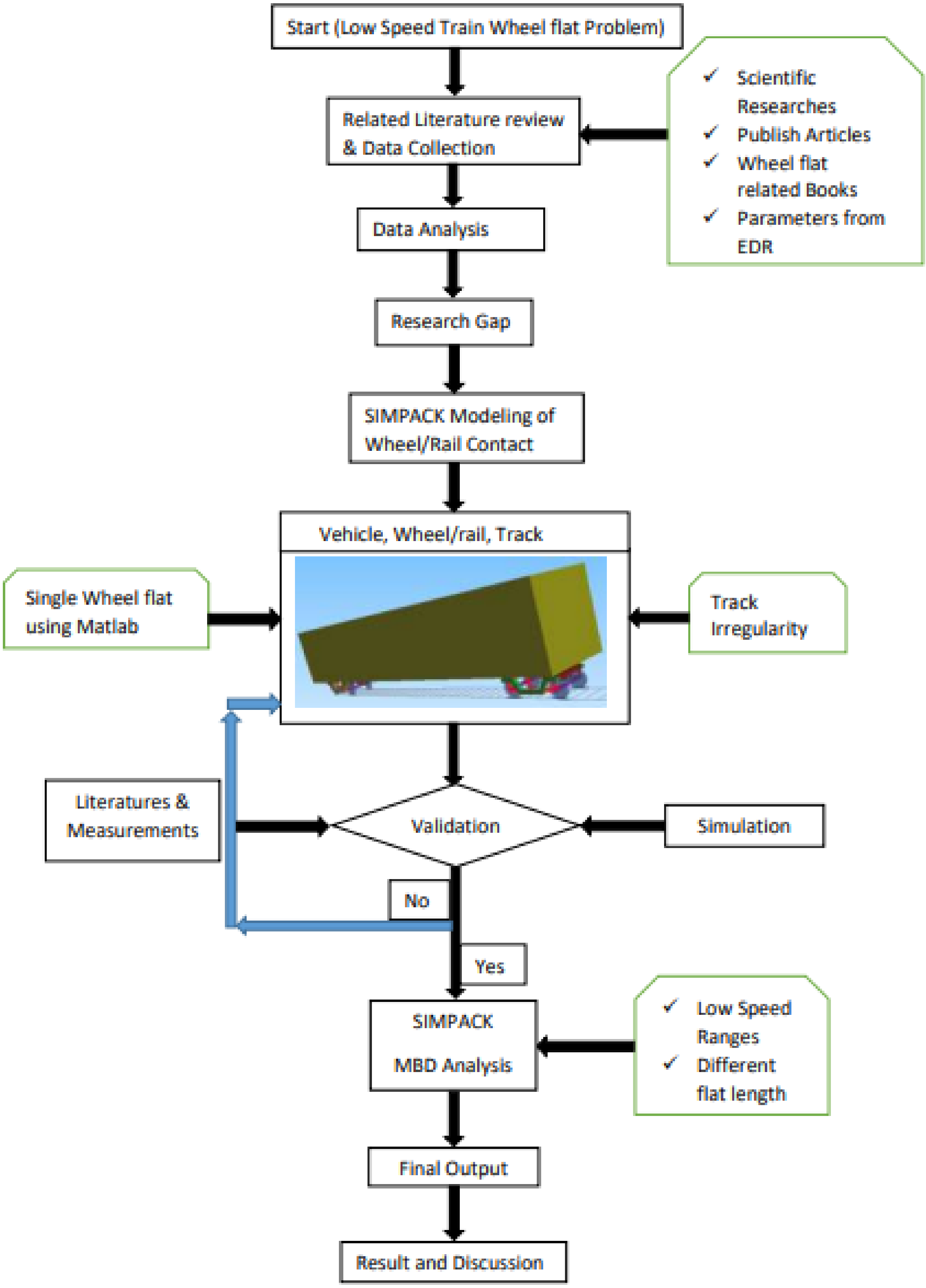


Figure 21: Methodology Flow Chart

3.1 Data collection

In this phase, the necessary data for the research was collected using secondary data collection method from Ethio-Djibouti Railway and other available sources, including:-

- Detail studying about the wheel flat from related published articles, books, and scientific researches.
- Site visiting of Ethio-Djibouti Railway train to observe the layout of wheel/rail profile and study wheel flat occurrence.
- Taking the recorded data of Ethio-Djibouti Railway on the current performance of the train wheels and the effect encountered in the vehicles & its components due to wheel flat occurred in the wheel.

3.2 Data Analysis

In this analysis, Multibody dynamics Simulation (MBS) is used to simulate wheel/rail collisions caused by wheel flat through SIMPAK by considering Rigid wheelset and track irregularities, then validate the result with available measurement data and related literature.

Table 3: Significant parameters for EDR of railway vehicles used in the present research.

Parameters	**Value**	**Unit**	**Parameters**	**Value**	**Unit**
Car body mass	33740	kg	Primary spring stiffness along x	31391000	N/m^2
Car body roll moment of inertia	56932	kgm^2	Primary spring stiffness along y	11500000	N/m^2
Car body pitch moment of inertia	1307220	kgm^2	Primary spring stiffness along z	260000	N/m^2
Car body yaw moment of inertia	1309744	kgm^2	Primary damping along x	15000	N.S/m
Bogie Frame mass	300	Kg	Primary damping along y	500000	N.S/m
Bogie Frame roll moment of inertia	1713	kgm^2	Primary damping along z	20000	N.S/m
Bogie Frame pitch moment of inertia	3206	kgm^2	Secondary spring stiffness along x	160000	N/m^2
Bogie Frame yaw moment of inertia	4763	kgm^2	Secondary spring stiffness along y	200000	N/m^2
Wheelset mass	1600	Kg	Secondary spring stiffness along z	450000	N/m^2
Wheelset roll moment of inertia	1271	kgm^2	Secondary damper along x	32000	N.S/m
Wheelset pitch moment of inertia	117	kgm^2	Secondary damper along y	1000000	N.S/m
Wheelset yaw moment of inertia	1271	kgm^2	Secondary damper along z	59000	N.S/m
Wheelset shaft length	2	m	Nominal wheel radius	0.46	M
Wheelset shaft outside diameter	0.18	m	Half of the lateral distance between wheel/rail contact points	1.25	M
Wheelset shaft inside diameter	0.014	m	Lateral Wheel Distance	0.75	M

Processes used in the analysis are given below:-

1. A typical EDR low-speed vehicle model is constructed using SIMPACK commercial Software package

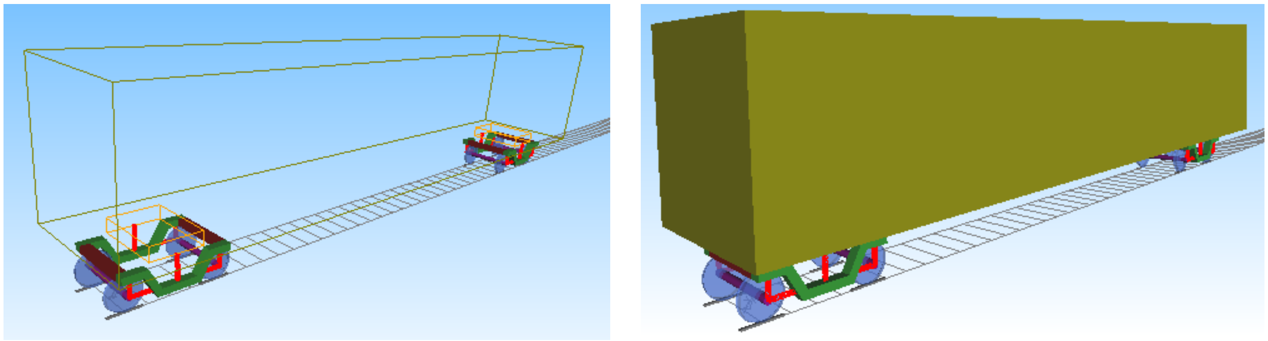


Figure 22: Typical vehicle model using SIMPAK

Preparing MATLAB Code to estimate the wheel flat size,the code includes

- Standard wheel profile of EDR Train Wheels
- Wheel Flat with different flat lengths for analysis
- The general equation for wheel flat function due to the flats

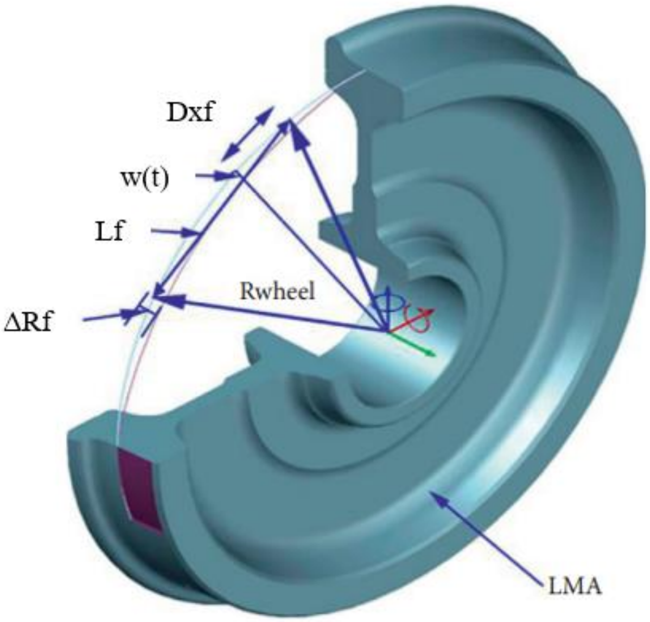


Figure 23: A railway wheel with a single haversine-type flat [5]

The wheelflat function $w(t)$ given by[3]

$$w(t) = 0.5 * \Delta Rf\left(1 - \cos\left(\frac{2\Pi Dxf}{Lf}\right)\right) \qquad \text{Eq 3}$$

$$\Delta Rf = \frac{Lf^2}{16Wrn} \qquad \text{Eq 4}$$

Where Wrn-Nominal wheel radius, ΔRf-Change of nominal radius, Lf-wheel flat length and Dxf-Discretization function of specific wheel flat

By analyzing the MATLAB Code, prepared different wheel flat lengths will get the relationships between the discretized specific wheel flat and the function (the rate of change of nominal radius due to the particular flat length)

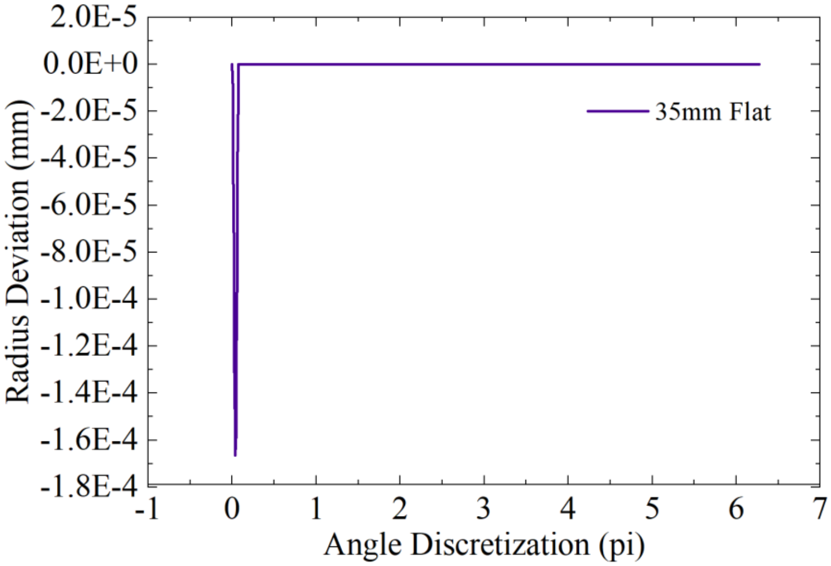


Figure 24: Sample results of MATLAB for Wheel flat function for 35mm Wheel flat

Providing the MATLAB result to Simpack Model to estimate the wheel flat size as an input function for the analysis.

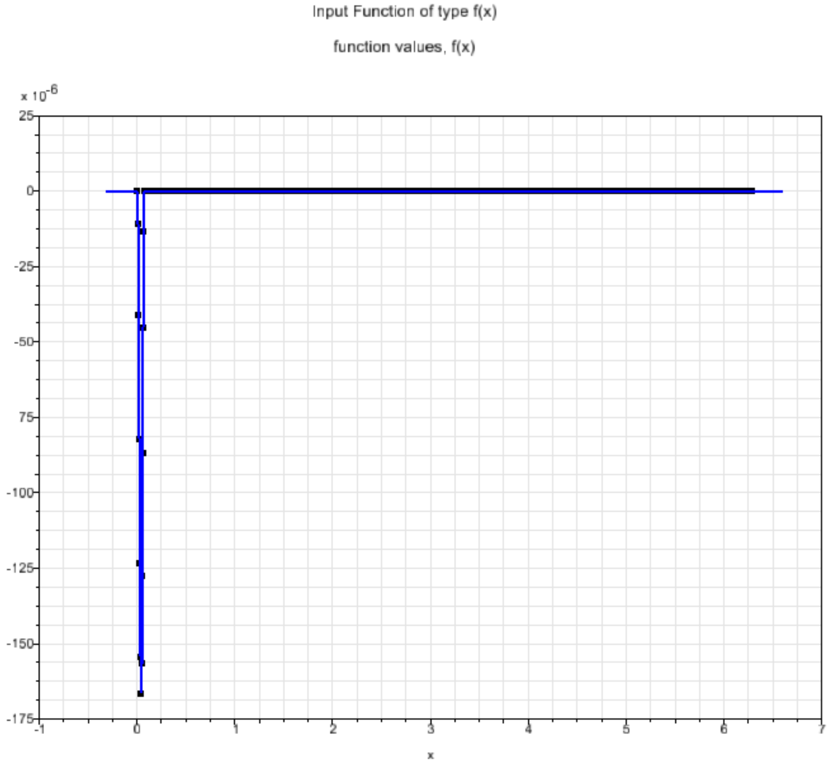


Figure 25: Typical Input Function property for wheel flat of 35mm from SIMPACK

2. Inserting Track irregularity Data to the model for the analysis

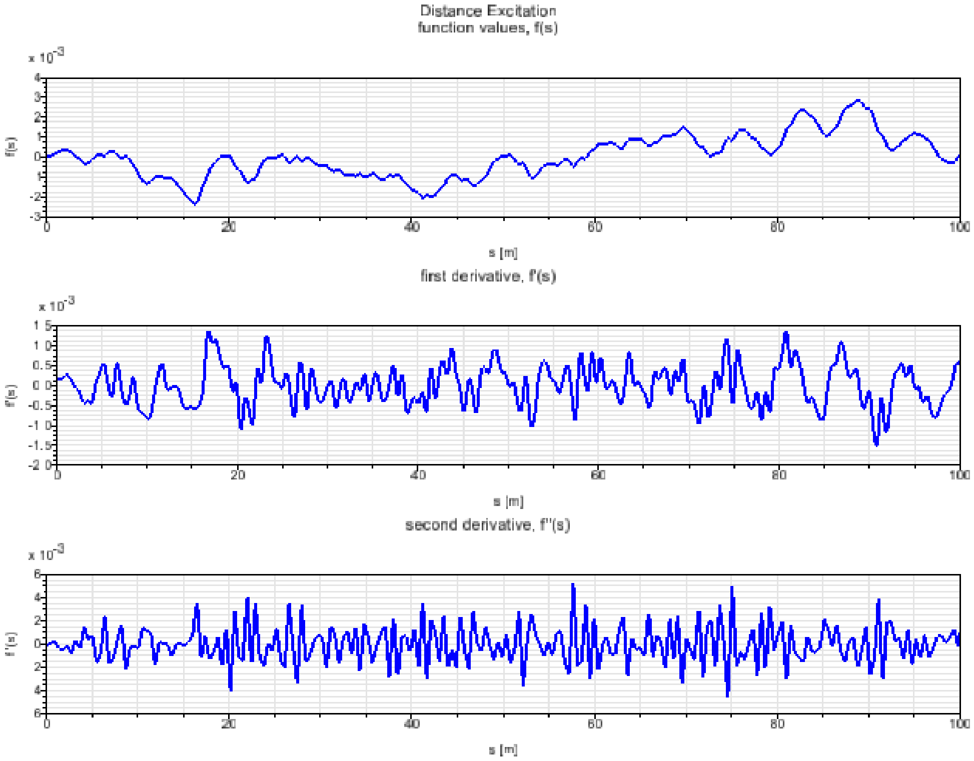


Figure 26: Sample Track Irregularity -Vertical left[5]

3.3 Simpack MBD Analysis

The finding of this analysis includes-

✓ Maximum vertical impact force as a function of flat length and Train low speeds
✓ Wheel-rail impact as a function of time
✓ Maximum vertical impact force as a function axle load
✓ Ride Index or Comfort level
✓ Acceleration, Amplitude and Power Spectrum Density(PSD)

○ Safe Wheel ● Wheel with Flat

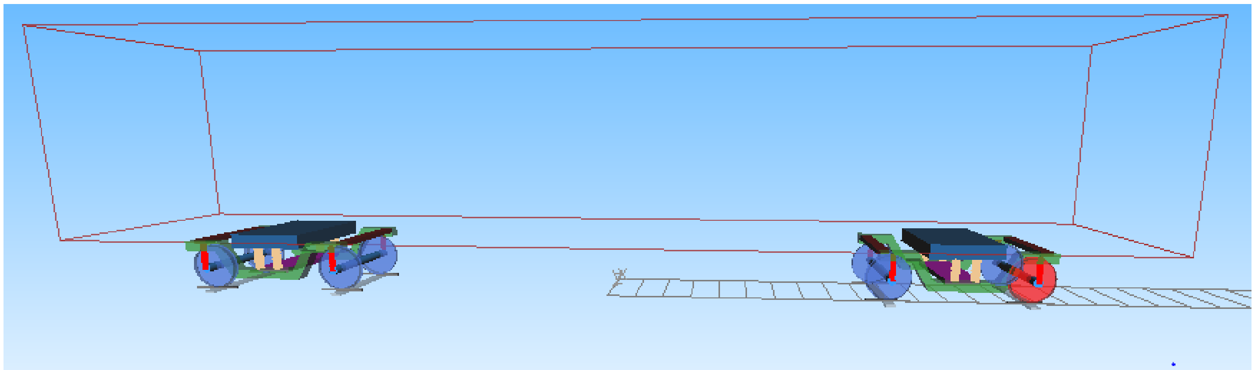


Figure 27: Model of Testing Coach

The effects of speed and wheel flat lengths on the dynamic safety and performance of the vehicle components, such as dynamic impact load, train acceleration, comfort level/ride index, and stability, will be studied by analyzing the above model with various low speed ranges and wheel flat lengths of EDR trains. These effects will be presented in tables and figures. Then using these results validation will be made to compare the result from the analysis with the standard and available experimental results.

Chapter 4 - Results and Discussion

4.1 Simulation Results

A wheel with a 10mm flat defect and a deep groove was found during the site visit for EDR train wheels, as shown in figure 6. To analyze severe cases, a wheel flat length of 25mm to 85mm were used in these scenario.

As shown in Table 4, various low speed ranges from 40 km/hr to 100 km/hr and wheel flat lengths from 25mm to 85mm were taken into consideration when analyzing the thesis work in order to study low-speed train dynamic performance due to wheel flat. Using this various speed and flat lengths, the effect of speed and wheel flat lengths were also examined.

Table 4: Simulation Parameters

No	**Low-speed Ranges of EDR Train Coach**	**Wheel Flat Lengths**
1	40km/h(11.111m/s)	25mm
2	50km/h(13.888m/s)	35mm
3	60km/h(16.667m/s)	45mm
4	70km/h(19.444m/s)	55mm
5	80km/h(22.222m/s)	65mm
6	90km/h(25 m/s)	75mm
7	100km/h(27.777m/s)	85mm

Based on these parameters, the Multibody Dynamics Simulation (MBS) was performed, and the simulation results were generated by adding the various wheel flat lengths indicated above to the right wheel of the testing coach's front wheelset with varied speeds and from the results it was able to determine the impact force, vertical acceleration, and ride index for each running speed with various wheel flat lengths as shown in the case simulation results below:

Case – 1: Varation of Vertical Wheel Force with respect to track irregularity

As demonstrated in Figure 28, a Multibody Dynamics Simulation (MBS) was performed using a test coach traveling at 40 km/hr without taking into account both wheel flat and track irregularities in Figure 28 (a) and then considering track irregularities without wheel flat in Figure 28 (b). Based on the results, an impact force for a passenger coach traveling at 40 km/hr without both wheel flat and track irregularity was constant at 50 kN and when track irregularity was taken into account, the value changed, reached a maximum value of 51.45 kN, demonstrating that track exitation increases the impact force.

- **Vertical wheel Force (Q)**

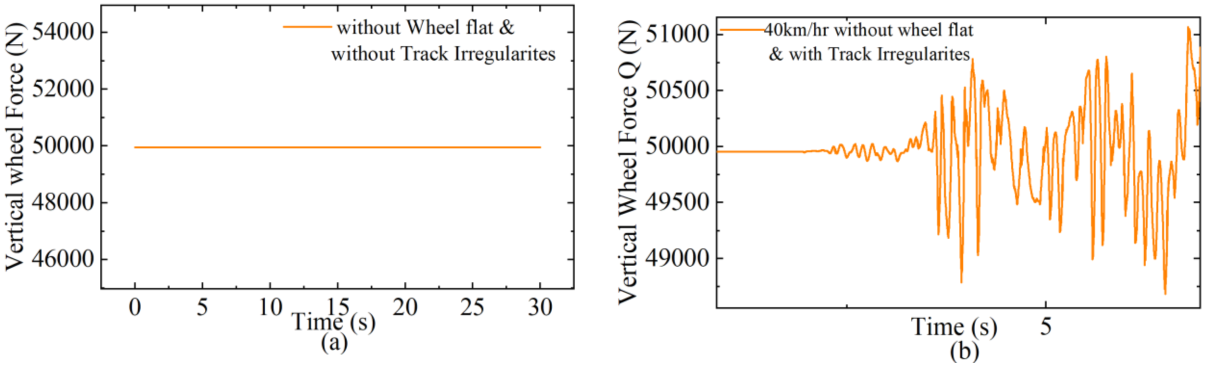


Figure 28: Vertical Wheel Force Q for the test wheel 1 a) without both wheel flat & track irregularity b) without wheel flat & with track irregularity

Case – 2: Varation of Vertical Wheel Force with respect wheel flat

In this specific simulation test to study the influences of wheel flat, a Multibody Dynamics Simulation (MBS) were carried out on a test coach moving at a speed of 70 km/h with and without wheel flat by considering track irregularity.

Using this simulation, we were able to derive results for the impact force which shows that an impact force for a passenger coach traveling at 70 km/hr without wheel flat has a maximum value of 53 kN as showen in the Figure 29 (a) and when wheel flat was taken into account, the value changed, reached a maximum value of 362 kN as shown in the Figure 29 (b), demonstrating that wheel flat has a significant effect on the vertical impact force results above the warning and alarm limit described by Matthias Asplund [7].

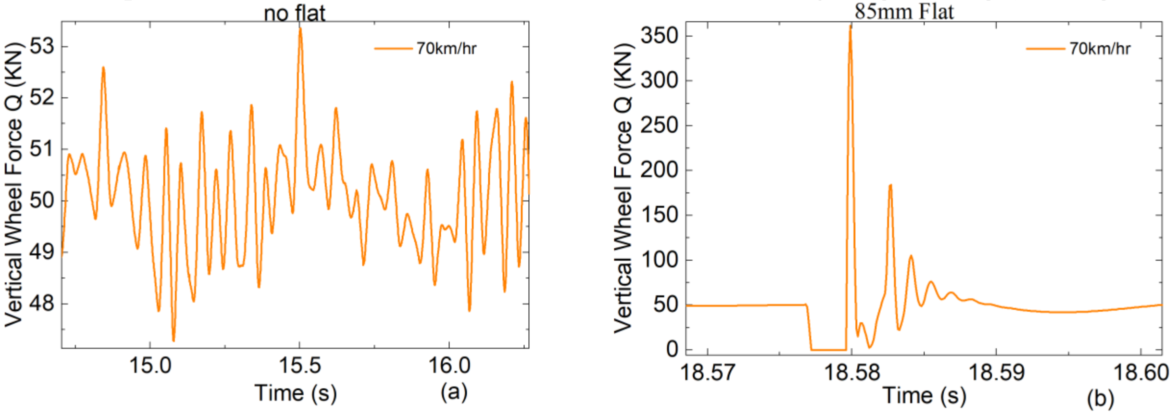


Figure 29: Vertical Wheel Force Q for the test wheel 1 a) without wheel flat b) with wheel flat

For the subsequent cases a Multibody Dynamics Simulation (MBS) were carried out by taking track irregularity into consideration and from the results it was able to determine the impact force, vertical acceleration, and ride index for each running speed with various wheel flat lengths.

Case – 3: Varation of Vertical Wheel Force, Acceleration and Ride index with respect to different running speed at a specfic wheel flat length

Results for impact force,vertical acceleration, and ride index for each running speeds were obtained from this sample simulation. Figure 30 and Figure 31 shows the impact load and vertical acceleration characteristics for each running speed respectively using identical flat lengths of 85 mm. Tables 5 and 6 presents the maximum values of the aforementioned results, respectively.

➢ Vertical wheel Force (Q)

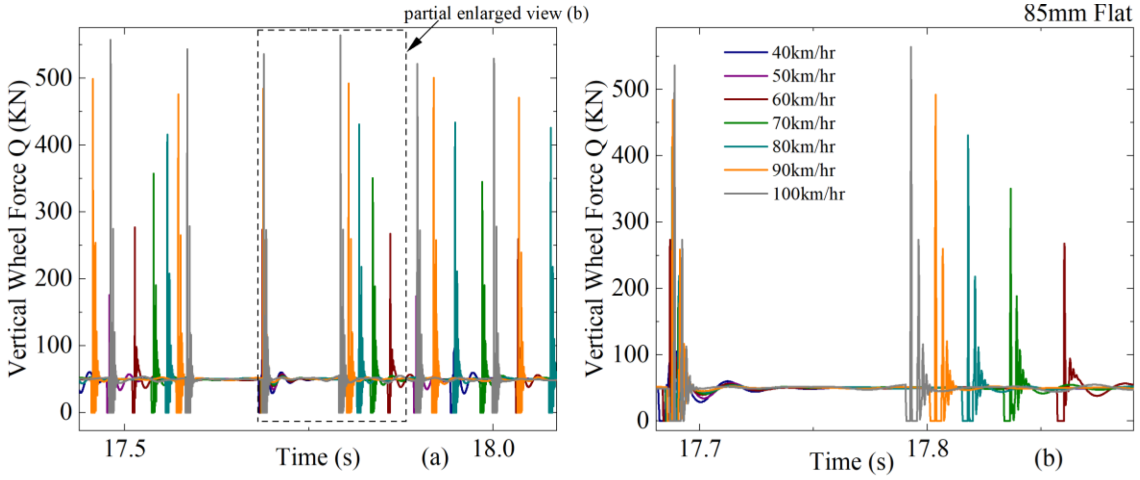


Figure 30: Vertical Wheel Force Q for the test wheel (Right wheel of the first wheelset) with 85mm wheel flat at different low speed ranges from 40km/hr-100km/hr

Table 5: Summary of Maximum Vertical Wheel force Q for 85mm wheel flat

No.	Running Velocity(km/hr)	Maximum Vertical Wheel Force Q(kN)
1	40	107.326
2	50	186.576
3	60	277.338
4	70	361.615
5	80	438.436
6	90	506.189
7	100	564.314

- **Acceleration and Ride Index**

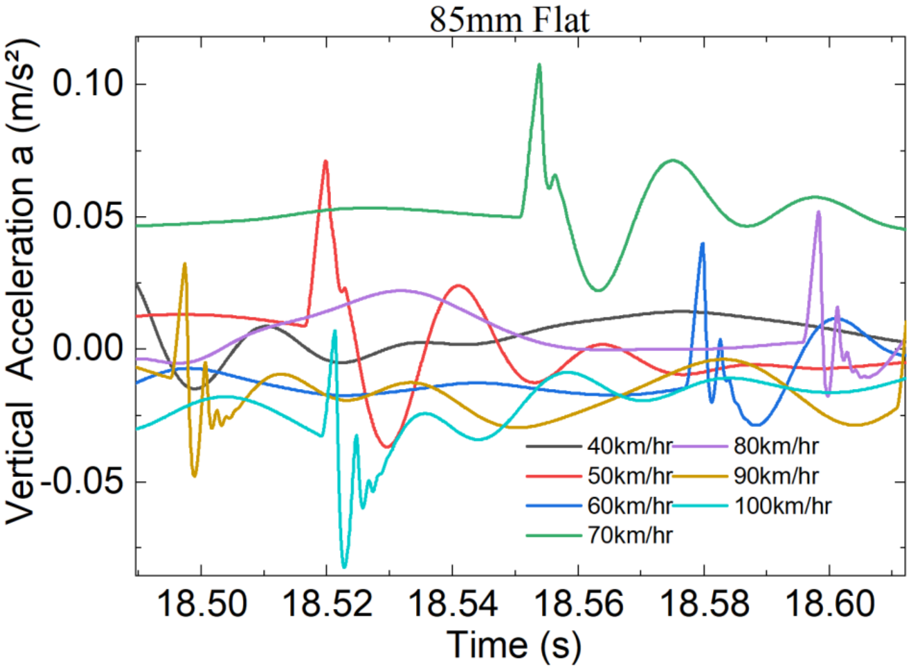


Figure 31: Car body Vertical Acceleration with 85mm wheel flat at different low speed ranges from 40km/hr-100km/hr

Table 6: Summary of Acceleration and Ride Index for 85mm wheel flat

No.	Running Velocity(km/hr)	Max Acceleration in Z (m/s²)	Ride Index,Vertical (m/s²)
1	40	0.0847964	0.882227
2	50	0.0971854	0.920029
3	60	0.107711	0.958899
4	70	0.105517	0.98693
5	80	0.097289	1.01186
6	90	0.088666	1.03784
7	100	0.087523	1.06449

From these results, we can show that for the wheel with a wheel flat of 85mm:-

- ✓ Maximum Vertical Wheel Force Q(N) and Ride Index (Vertical) increase with running speed from 40 km/hr to 100 km/hr.
- ✓ Maximum Vertical Acceleration likewise increases with running speed up to 70 km/hr, after which it reduces.

Case – 4: Varation of Vertical Wheel Force, Acceleration and Ride index with respect to wheel flat length at a specfic running speed

In this specific simulation test to study the influences of wheel flat length, a Multibody Dynamics Simulation (MBS) were carried out on a test coach moving at a speed of 70 km/h with various wheel flat lengths from 25 mm to 85 mm on the right wheels of the front wheelset and track irregularity was taken into account. Using this simulation, we were able to derive results for the impact force, vertical acceleration, and ride index for each wheel flat length. Figure 32 displays the characteristics of the impact load for each wheel flat length at a constant 70 km/hr running speed. The maximum values of the aforementioned results shown in Tables 7 and 8 respectively.

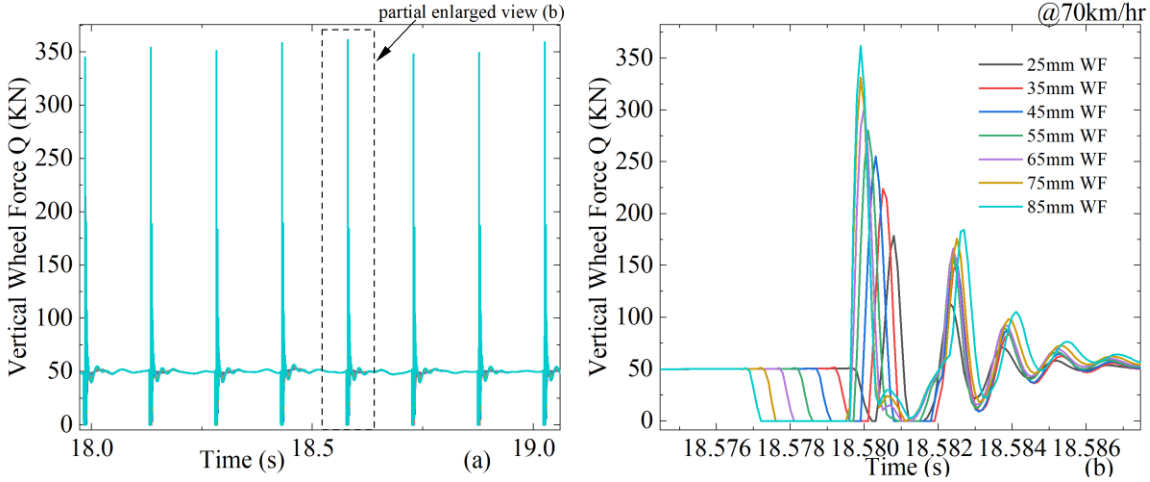


Figure 32: Vertical Wheel Force Q for the test wheel (Right wheel of the first wheelset) running at 70km/hr with different wheel flat ranges from 25mm-85mm

Table 7: Summary of Maximum Vertical Wheel force Q at a speed of 70km/hr

No.	Wheel flat lengths	Maximum Vertical Wheel Force Q(kN)
1	25mm	183.462
2	35mm	226.649
3	45mm	255.704
4	55mm	280.642
5	65mm	305.676
6	75mm	331.961
7	85mm	361.615

- **Acceleration and Ride Index**

Table 8: Summary of Acceleration and Ride Index at a speed of 70km/hr

No.	Wheel flat lengths	Max Acceleration in Z (m/s^2)	Ride Index,Vertical (m/s^2)
1	25mm	0.063008	0.978082
2	35mm	0.066405	0.978089
3	45mm	0.073365	0.978179
4	55mm	0.080905	0.978691
5	65mm	0.089002	0.980017
6	75mm	0.097271	0.98261
7	85mm	0.105517	0.98693

From these results, we can show that for the wheelset running at a running speed of 70km/hr

- ✓ Maximum Vertical Wheel Force Q(N) , Vertical acceleration and Ride Index increases with increasing wheel flat length from 25mm wheel flat to 85mm wheel flat running at the same running speed of 70km/hr.

Case – 5: Varation of Vertical Wheel Force with respect to low and high running speeds

This particular simulation test used to study the influences of running speeds other than low speeds as a comparison to check properties of Vertical Wheel Force at both low and high speeds with a wheel flat and to show the general properties of impact load due to wheel flat.

Here, a Multibody Dynamics Simulation (MBS) were performed on a test coach running for speed ranges from 40 km/h to 300 km/h with 75 mm and 85 mm wheel flat lengths on the right wheels of the front wheelset and track irregularity was taken. We were able to determine findings for the impact force for both wheel flat lengths using this simulation. The maximum values of the results displayed in Tables 9 along with the characteristics of the impact load for both wheel flat lengths utilizing different running speeds in Figure 33.

Table 9: Summary of Maximum Vertical Wheel force Q for 75mm and 85mm wheel flats

No.	Running Velocity(km/hr)	Maximum Vertical Wheel Force Q(kN)	
		75mm Flat	85mm Flat
1	40	96.1158	107.326
2	50	148.867	186.576
3	60	250.086	277.338
4	70	331.961	361.615
5	80	406.160	438.436
6	90	469.619	506.189
7	100	522.972	564.314
8	150	709.598	791.446
9	200	703.184	773.378
10	250	650.892	758.511
11	300	616.387	696.625

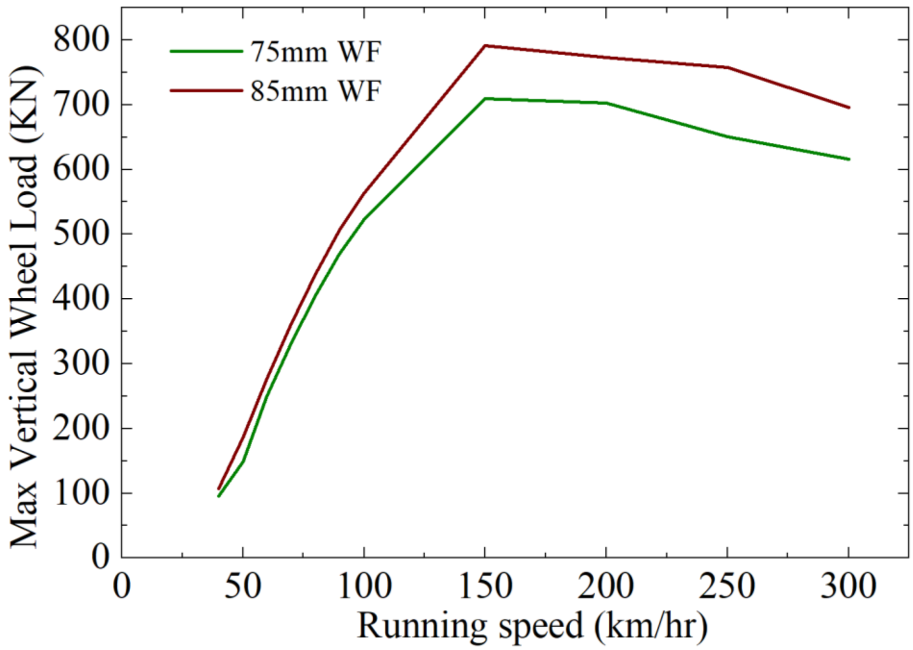


Figure 33: Maximum Vertical Wheel Force Q for the test wheel (Right wheel of the first wheelset) with 75mm and 85mm wheel flats at different speed ranges from 40km/hr-300km/h

The results shows that the impact load increases with increasing speed and reaches a maximum value at a certain speed, above which the impact load reduces slightly. This is due to wheel flying when a flat comes into contact at a relatively high speed. This phenomenon may be explained reasonably with the dynamic contact loss opinion [21, 22]: when the wheel flat impacted against the rail, the impulse of the wheel rapidly transferred to the momentums of the wheel and rail; then the wheel tended to move upwards while the rail tended to move downwards, resulting in the loss of dynamic contact.

For the lower train speed, the initial impulse of the wheel is low, and the momentums of the wheel and rail are also low; the quasi-static wheel load can maintain the wheel-rail contact, so the wheel-rail impact force increases with the train speed. However, for the higher speed case, the large impulse induces the large momentums of the wheel and rail; during the downward movement of the rail, the wheel still keeps falling for a while because of its large inertia, so the maximum impact force is attenuated, as a result of the reduction of the dynamic contact [16].

When the running speed increases up to 150km/hr Maximum Vertical Wheel Force Q also increases, and then it reduces after 150km/hr and it has less impact or effect due to wheel-rail contact loss after this speed; for example, the peak value of Figure 33 is 552.972kN and 564.314kN for the wheel flats of 75mm and 85mm respectively running at a speed of 100km/hr and then it increased to 709.598kN and 791.446kN for the wheel flats of 75mm and 85mm respectively running at a speed of 150km/hr. Similarly Figure 33 illustrates that the maximum peak value for wheel flats of 75mm and 85mm is reduced to 616.387kN and 696.625kN ,respectively at a speed of 300km/hr.Therefore relation variation of both running speed and wheel flat length condition for Vertical Wheel Force is increased by 22.07% and 28.69% and then reduced by 13.13% and 11.98% for wheel flats of 75mm and 85mm, respectively.

4.2 Discussion of Simulation Results

4.2.1 Vertical Wheel Force

A Multibody Dynamics Simulation (MBS) were run on a test coach moving at a speed of 100 km/h to examine the effects of track irregularity on the vertical wheel force with different wheel flat lengths of 45mm, 65mm, and 85mm, respectively. The results shown in Figures 34 and 35 with and without track irregularity respectively.

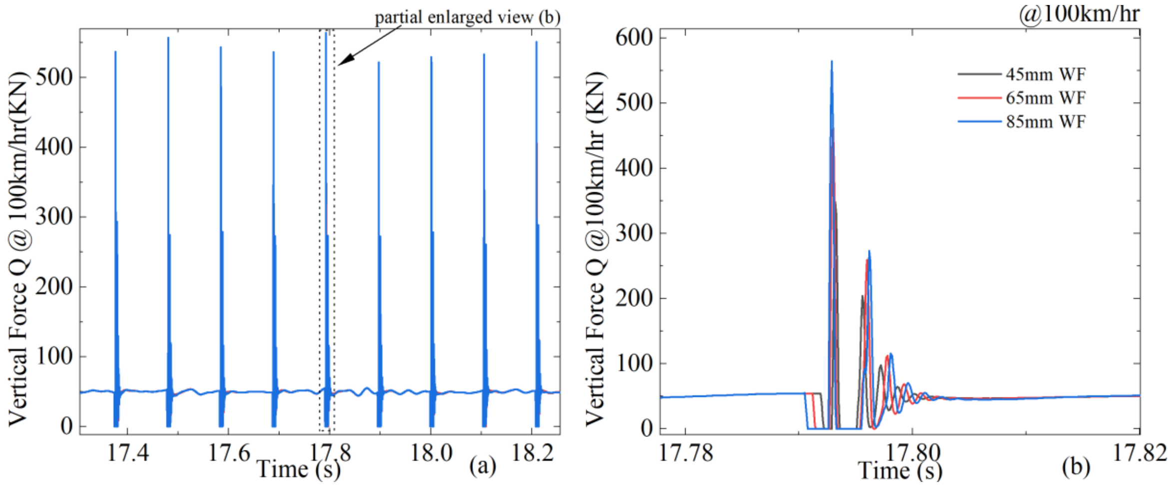


Figure 34: Vertical Force of 45mm, 65mm & 85mm wheel flat @100km/hr with track irregularity

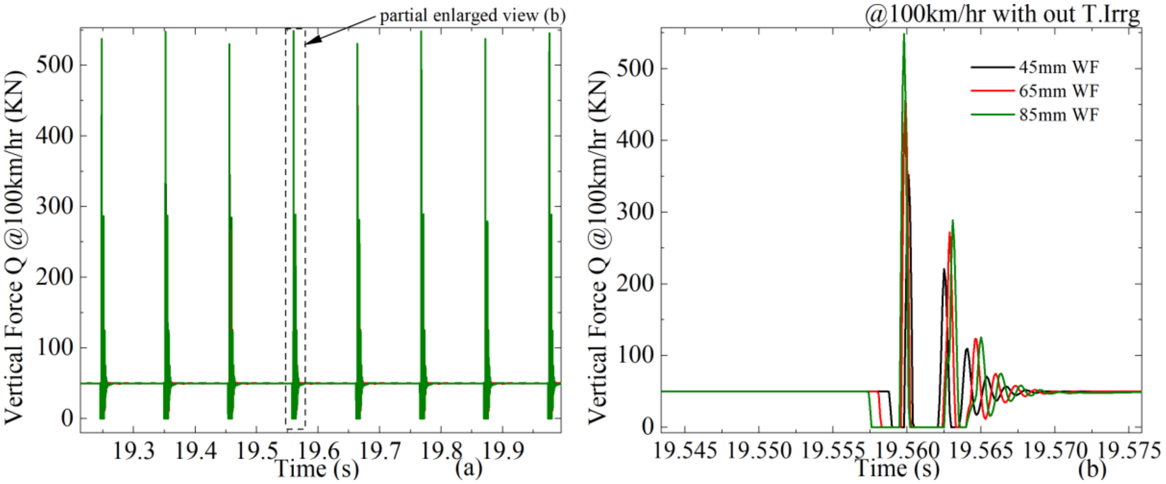


Figure 35: Vertical Force of 45mm, 65mm & 85mm wheel flat @100km/hr without track irregularity

The result shows that ,Vertical Wheel Force(Q) is maximum when the track is integrated with excitation, but when the track without excitation has less impact or effect, for example, the peak value of Figure 34 with track excitation is about 363.732kN, 473.826kN and 564.314kN for the wheel flats of 45mm, 65mm and 85mm respectively. Similarly, Figure 35 illustrates that the maximum peak value for wheel flats of without track excitation is about 45mm, 65mm and 85mm is 352.562kN, 463.121kN and 548.844kN respectively. Threfore relative variation of both track conditions for Vertical wheel Force(Q) is 3.07%, 2.25% and 2.74% for wheel flats of 45mm, 65mm and 85mm, respectively.

Summary of Maximum vertical load:

Results of the maximum vertical load measurements made on test simulations with wheel flat ranges between 25mm and 85 mm at speeds between 40km/hr and 100 km/hr shown in Table 10 below and plotted on Figure 36.

Table 10: Summary of Maximum Vertical Wheel force Q for wheel flat ranges from 25mm to 85mm at a speed range of 40km/hr to 100km/hr

		Maximum Vertical Wheel Force Q(kN) with wheel flat of						
No	Speed (km/hr)	25mmWF	35mmWF	45mmWF	55mmWF	65mmWF	75mmWF	85mmWF
1	40	100.854	88.494	76.1583	79.690	86.3551	96.1158	107.326
2	50	133.138	131.562	122.246	118.957	126.546	148.867	186.576
3	60	161.735	183.400	195.726	208.927	223.925	250.086	277.338
4	70	183.462	226.649	255.704	280.642	305.676	331.961	361.615
5	80	199.257	260.099	303.335	341.672	374.014	406.160	438.436
6	90	201.597	280.166	339.588	386.732	430.903	469.619	506.189
7	100	201.110	292.252	363.732	420.538	473.826	522.972	564.314

The above result shows that a railway vehicle with a wheel flat running at low speed have a signficant effect on the vertical impact force which leads to damage to the vehicle and track components as illustrated in Table 10 and discussed below:-

- ✓ For running speed of 40km/hr and 50km/hr with a wheel flat length from 25mm to 85mm the vertical wheel impact force is less than the Warning limit which is 155KN, implies that safe operating condition.
- ✓ For running speed of 60km/hr with a wheel flat from 25mm to 85mm the vertical wheel impact force exceeds Warning limit but less than the Alarm limit which is 320KN, implies that moderate operating condition.
- ✓ For running speed of 70km/hr with a wheel flat length up to 75mm the vertical wheel impact force exceeds Warning limit but less than the alarm limit, and above a 75mm wheel flat length vertical wheel impact force exceeds Alarm limit, implies that severe operating condition.
- ✓ For running speed of 80km/hr with a wheel flat length up to 55mm the vertical wheel impact force exceeds Warning limit but less than the alarm limit, and above a 55mm wheel flat length vertical wheel impact force exceeds Alarm limit, implies that severe operating condition.
- ✓ For running speed of 90km/hr and 100km/hr with a wheel flat length up to 45mm the vertical wheel impact force exceeds Warning limit but less than the alarm limit, and above a 45mm wheel flat length vertical wheel impact force exceeds Alarm limit, implies that severe operating condition.

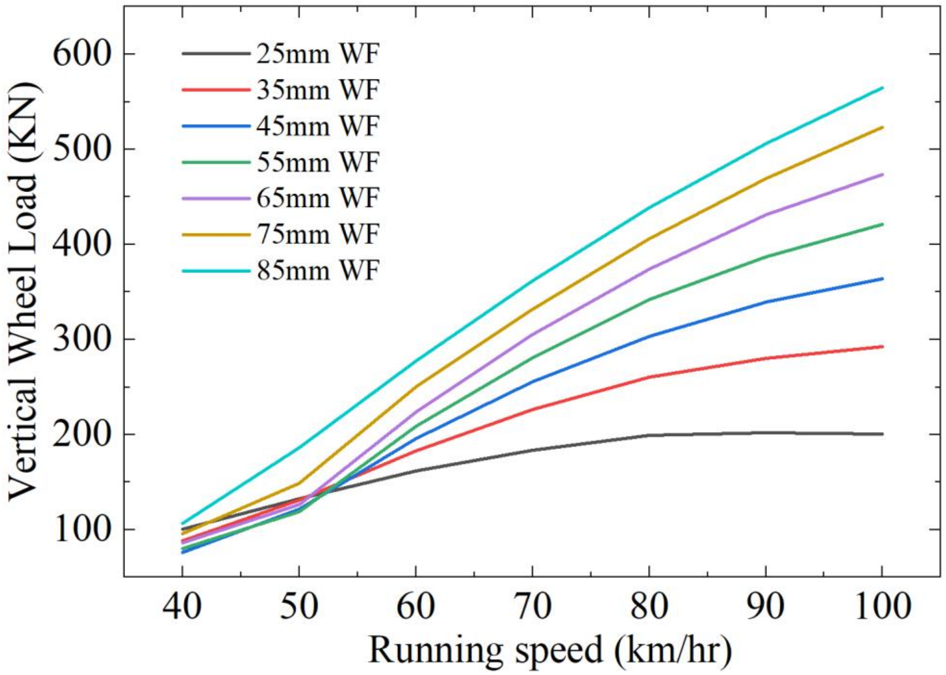


Figure 36 : Max Vertical Wheel Force Q for the test wheel (Right wheel of the first wheelset) running at speed ranges from 40km/hr to 100km/hr with different wheel flat ranges from 25mm-85mm

Influence of Flat Length on Vertical Wheel Force Q is that it has a maximum effect when the wheel flat length increases, but when the wheel flat length reduces, it has less impact or effect. And Influence of Running speed on Vertical Wheel Force Q is that, when the running speed increases up to 150km/hr, Vertical Wheel Force Q also increases. Then it reduces after 150km/hr due to wheel-rail contact loss after this speed, as illustrated in the case-5 and Figure 33. Still, for the low speed ranges 40km/hr-100km/hr Vertical Wheel Force Q increases with running speed, for example, the peak value of Figure 36 is 133.14kN, 131.56kN, 122.25kN, 118.95kN, 126.54kN, 148.86kN &186.57kN for the wheel flats of 25mm, 35mm, 45mm, 55mm, 65mm, 75mm and 85mm respectively running at a speed of 50km/hr. Whereas Figure 36 also illustrates that the maximum values for wheel flats of 25mm, 35mm, 45mm, 55mm, 65mm, 75mm and 85mm is 201.11kN, 292.25kN, 363.73kN, 420.54kN, 473.83kN, 522.97kN & 564.31kN respectively at a running speed of 100km/hr. Therefore relation variation of both running speed and wheel flat length condition for maximum vertical wheel force (Q) is 33.79%, 54.98%, 66.38%, 71.71%, 73.29%, 71.53% and 66.93% for wheel flats of 25mm, 35mm, 45mm, 55mm, 65mm, 75mm and 85mm respectively.

4.2.2 Ride Index 45mm, 65mm & 85mm Wheel Flat

In order to investigate the impacts of track irregularity on the Ride index with various wheel flat lengths of 45mm, 65mm, and 85mm, respectively, a Multibody Dynamics Simulation (MBS) were run on a test coach travelling at speeds range from 40km/h to 100km/h. Figures 37 indicate the outcomes.

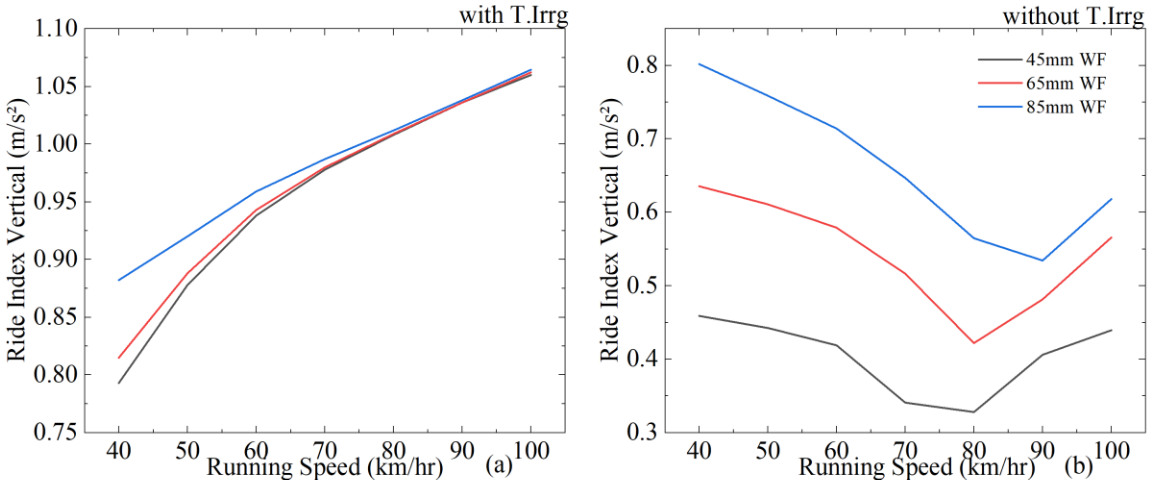


Figure 37: a) Ride Index with Track irregularity, b) Ride Index without Track irregularity

Ride Index is maximum when the track is integrated with excitation. Still, when the track without excitation has less impact or effect, for example, the peak value of Figure 37 a**)** is 1.060m/s², 1.062m/s², and 1.064m/s², for the wheel flats of 45mm, 65mm and 85mm respectively running at a speed of 100km/hr with track irregularity. Figure 37 b) illustrates that the maximum peak value for 45mm, 65mm and 85mm wheel flats is 0.439 m/s², 0.565 m/s² & 0.618 m/s² respetivey running at a speed of 100km/hr without track irregularity. Therefore relative variation of both track conditions for Ride Index is 58.58%, 46.79%, and 41.91% for wheel flats of 45mm, 65mm, and 85mm, respectively

4.2.3 Dynamic Response

4.2.3.1 Vertical Acceleration

To investigate the characteristics of vertical acceleration with different wheel flat lengths and running speeds, a Multibody Dynamics Simulation (MBS) were conducted on a test coach moves at speeds of 70 km/h and 100 km/h with various wheel flat lengths of 45mm, 65mm, and 85mm respectively. The results shown in Figures 38.

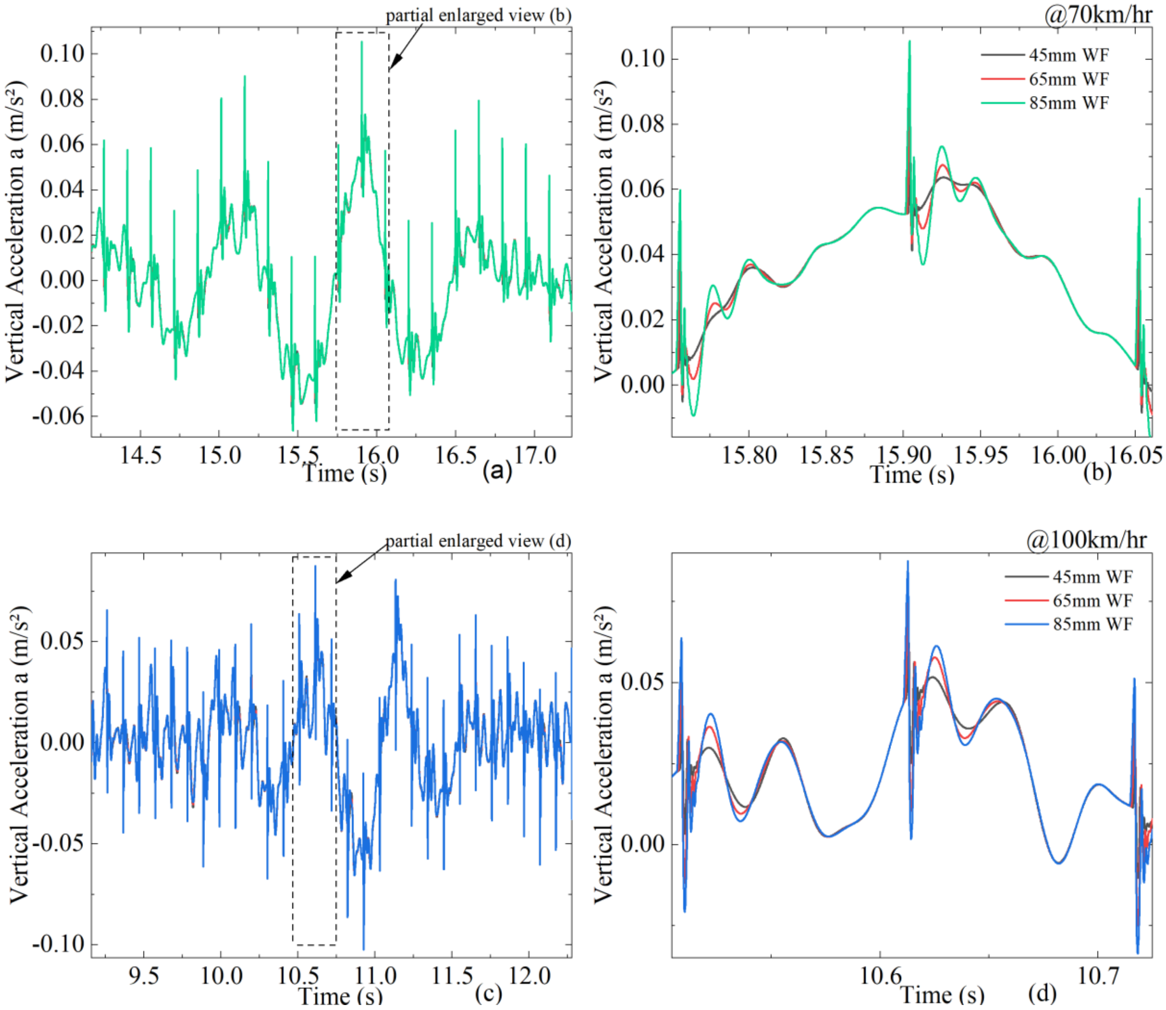


Figure 38: a & b) Vertical Acceleration @70km/hr, c & d) Vertical Acceleration @100km/hr

When the running speed increases up to 70km/hr, Car body vertical acceleration also increases, and then it reduces after 70km/hr, for example, the peak value of Figure 38 a) & b) is 0.073 m/s^2,0.089 m/s^2 and 0.105 m/s^2 45mm,65mm and 85mm wheel flats respectively running at a speed of 70km/hr. Similarly, Figure 38 c) & d) illustrates that the maximum peak value for 45mm,65mm and 85mm wheel flats is 0.063 m/s^2, 0.075 m/s^2 & 0.087 m/s^2 respectively at a speed of 100km/hr.Therefore relation variation of both running speed and wheel flat length condition for vertical acceleration is 13.69%,15.73% and 17.14% for wheel flats of 45mm,65mm and 85mm, respectively.

Summary of Car body Maximum vertical Acceleration

Table 11 below and Figure 39 illustrate the results of the maximum vertical acceleration measurements performed on test simulations with wheel flat ranges between 25 mm and 85 mm at speeds between 40km/hr and 100km/hr

Table 11: Summary of Maximum Vertical Acceleration for wheel flat ranges from 25mm to 85mm at a speed range of 40km/hr to 100km/hr

		Maximum Vertical Acceleration (m/s^2) with wheel flat of						
No	Speed (km/hr)	25mmWF	35mmWF	45mmWF	55mmWF	65mmWF	75mmWF	85mm WF
1	40	0.0276802	0.0317457	0.037351	0.0460791	0.0563612	0.0692274	0.0847964
2	50	0.0418085	0.047809	0.054676	0.0629638	0.0731018	0.0847645	0.0971854
3	60	0.0578319	0.0640956	0.071255	0.0795212	0.0885106	0.0972708	0.105517
4	70	0.0630833	0.0664053	0.073365	0.0809046	0.0890022	0.0980043	0.107711
5	80	0.0628101	0.0625269	0.068172	0.0751643	0.0823357	0.0896532	0.097289
6	90	0.0612909	0.0612731	0.062496	0.0685513	0.0750569	0.0819242	0.088666
7	100	0.0630076	0.0633199	0.063913	0.0689301	0.0750599	0.081426	0.087523

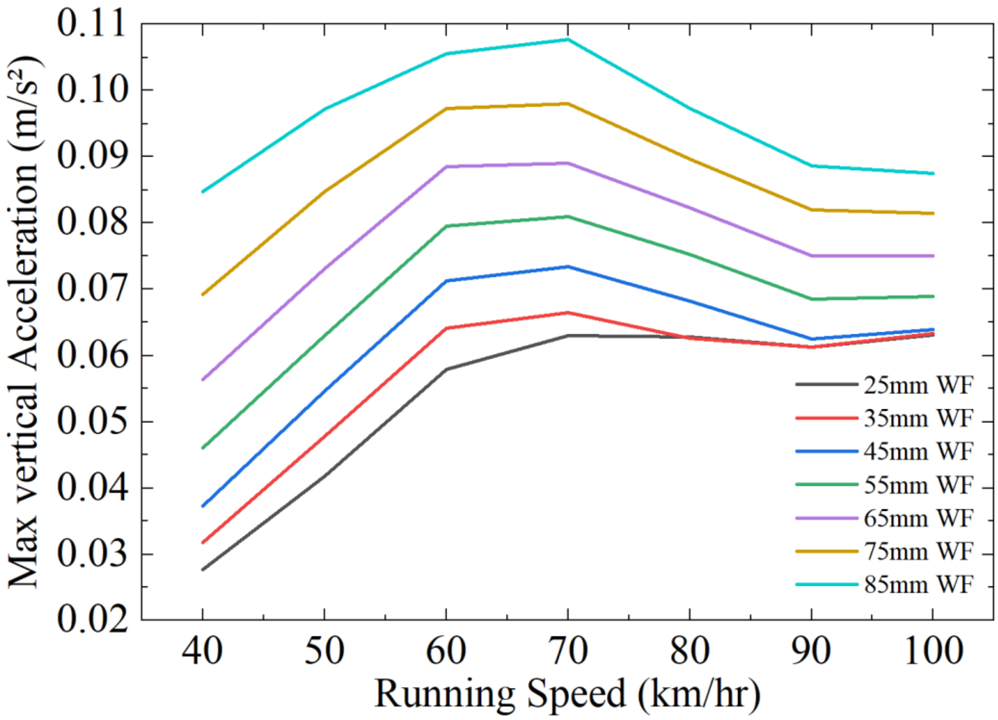


Figure 39: Max Vertical Acceleration for the test wheel (Right wheel of the first wheelset) running at speed ranges from 40km/hr to 100km/hr with different wheel flat ranges from 25mm-85mm

Based on the results, the influence of flat length on vertical acceleration is that it has a maximum effect when wheel flat length increases, but when the flat wheel length reduces, it has less impact or effect. And Influence of running speed on vertical acceleration is that when the running speed increases up to 70km/hr, vertical acceleration also increases and then it reduces after 70km/hr; for example, the peak value of Figure 39 is 0.042m/s², 0.048m/s², 0.054m/s², 0.063m/s², 0.073m/s², 0.085m/s² & 0.097m/s² for the wheel flats of 25mm, 35mm, 45mm, 55mm, 65mm,75mm and 85mm respectively running at a speed of 50km/hr and then it increased to 0.06m/s², 0.066m/s², 0.073m/s², 0.081m/s², 0.089m/s², 0.098m/s² & 0.107m/s² respectively running at a speed of 70km/hr. Similarly, Figure 39 illustrates that the maximum peak value for wheel flats of 25mm, 35mm, 45mm, 55mm, 65mm,75mm, and 85mm is reduced to 0.062m/s², 0.063m/s², 0.064m/s², 0.069m/s², 0.075m/s², 0.081m/s² & 0.087m/s² respectively at a speed of 100km/hr. Therefore relative variation of both running speed and wheel flat length condition for Vertical acceleration is increased by 33.33%, 27.27%, 26.02%, 22.22%, 17.97%, 13.26% and 9.34% and then reduced by 1.58%, 4.54%, 12.32%, 14.81%, 15.73%, 17.34% and 18.69%% for wheel flats of 25mm, 35mm, 45mm, 55mm, 65mm,75mm and 85mm respectively.

4.2.3.2 Vertical Acceleration Frequency Domain (Amplitude)

A Multibody Dynamics Simulation (MBS) were performed on a test coach moving at speeds of 40km/hr, 70km/hr, and 100km/hr with various wheel flat lengths of 45mm, 65mm, and 85mm, respectively, to examine the features of amplitude with varying wheel flat lengths and running speeds. The outcomes displayed in the following Figures 40:-

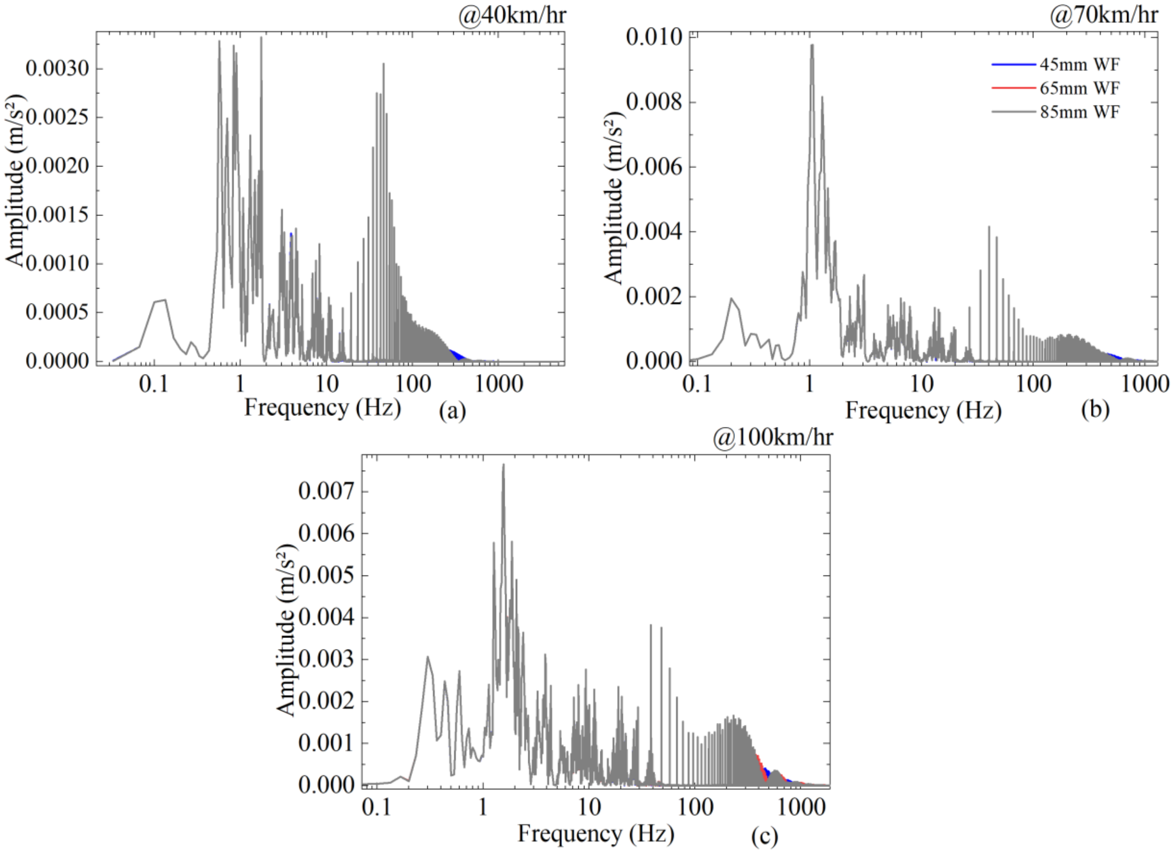


Figure 40: Vertical Amplitude @40km/hr, @70km/hr & @100km/hr

As per the results, the effects of flat length on vertical acceleration amplitude are not much different when the flat size increases. And Influence of Running speed on the amplitude of a vertical acceleration is that when the running speed increases up to 70km/hr, amplitude also increases and then it reduces after 70km/hr; for example, the peak value of Figure 40 a) & b) is equivalent to 0.0033m/s² for the wheel flats of 45mm, 65mm and 85mm running at a speed of 40km/hr and then it increased to 0.00978m/s² running at a speed of 70km/hr respectively. Similarly, Figure 40 c) illustrates that the maximum peak value for wheel flats of 45mm, 65mm and 85mm is reduced to 0.00766m/s², running at 100km/hr. Therefore relation variation of both running speed and wheel flat length condition for Amplitude of a Vertical Acceleration is increased by 66.25% and then reduced by 21.67% for wheel flats of 45mm, 65mm and 85mm.

4.2.3.3 Vertical Acceleration Power Spectrum Density (PSD)

To investigate the characteristics of Power Spectrum Density (PSD) with various wheel flat lengths and running speeds, a Multibody Dynamics Simulation (MBS) were carried out on a test coach moving at speeds of 40 km/hr, 70 km/hr, and 100 km/hr with various wheel flat lengths of 45 mm, 65 mm, and 85 mm, respectively. Figure 41 shows the results in the following ways: -

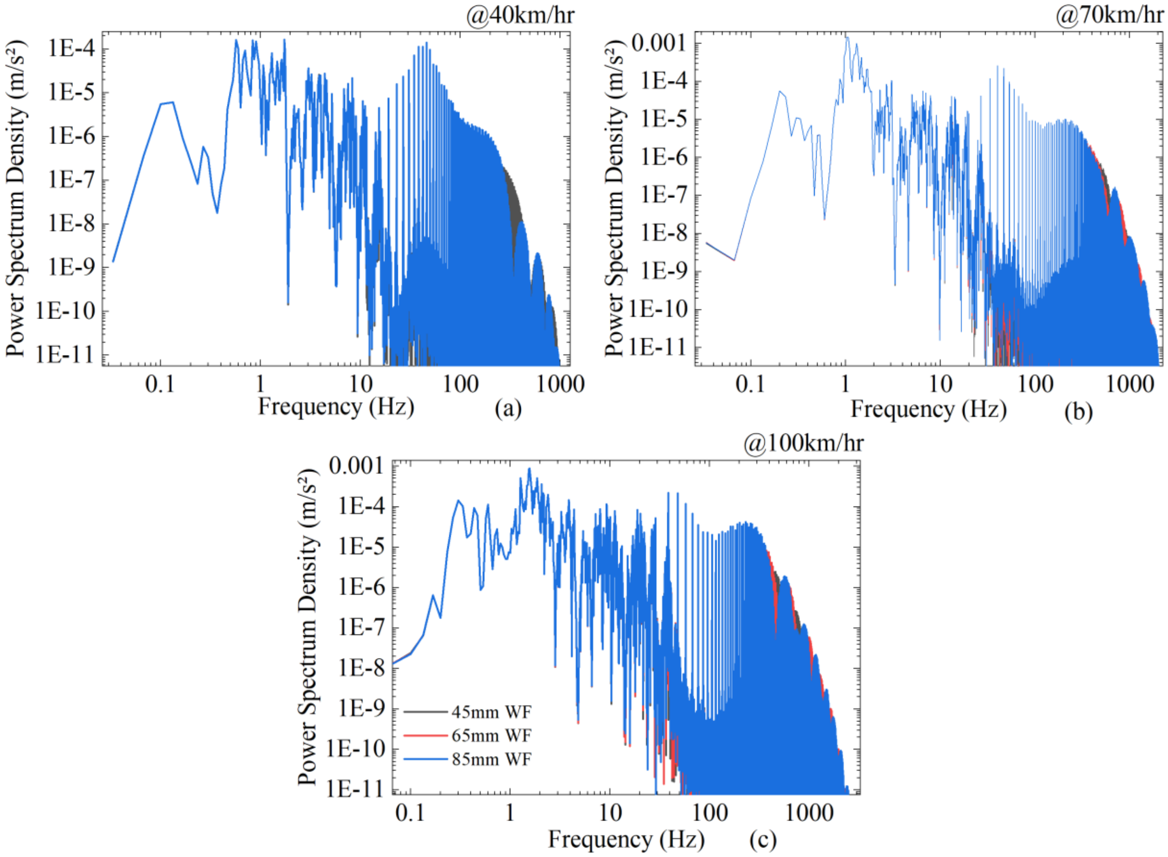


Figure 41: Vertical Acceleration PSD @40km/hr, @70km/hr & @100km/hr

Influence of Flat Length on Power Spectrum Density (PSD) of a vertical acceleration is not much different when flat size increases. And Influence of Running speed on Power Spectrum Density(PSD) of a vertical acceleration is that, when the running speed increases up to 70km/hr Power Spectrum Density(PSD) also increases and then it reduces after 70km/hr, for example, the peak value of Figure 41 a) & b) is equivalent to 0.0001656m/s² for the wheel flats of 45mm, 65mm and 85mm running at a speed of 40km/hr and then it increased to 0.001436m/s² running at a speed of 70km/hr. Similarly, Figure 41 c) illustrates that the maximum peak value for wheel flats of 45mm, 65mm, and 85mm is reduced to 0.00088m/s², running at a 100km/hr speed. Therefore relation variation of running speed and wheel flat length condition for Power Spectrum Density(PSD) of a Vertical Acceleration is increased by 88.46% and then reduced by 38.71% for wheel flats of 45mm, 65mm, and 85mm.

4.3 Validation

Simulated findings must be compared with those acquired from actual Measurement to validate the current Simpack MBD model of the EDR low-speed vehicle. Results of vertical wheel-rail contact force measured in one instrumented sleeper bay of the wheel impact load detector on Svealandsbanan (2000)[23] in which a feld measurements were conducted in Sweden in the spring of 2000 on the main line between Eskilstuna and SoÈ dertaÈ lje were used for the validation of the current Simpack MBD model.

The rail vehicle was moved at a maximum speed of 50 km/h over a straight truck with 100mm wheelflat, and we obtained vertical wheel-rail contact force to demonstrate the accuracy of the simulation.

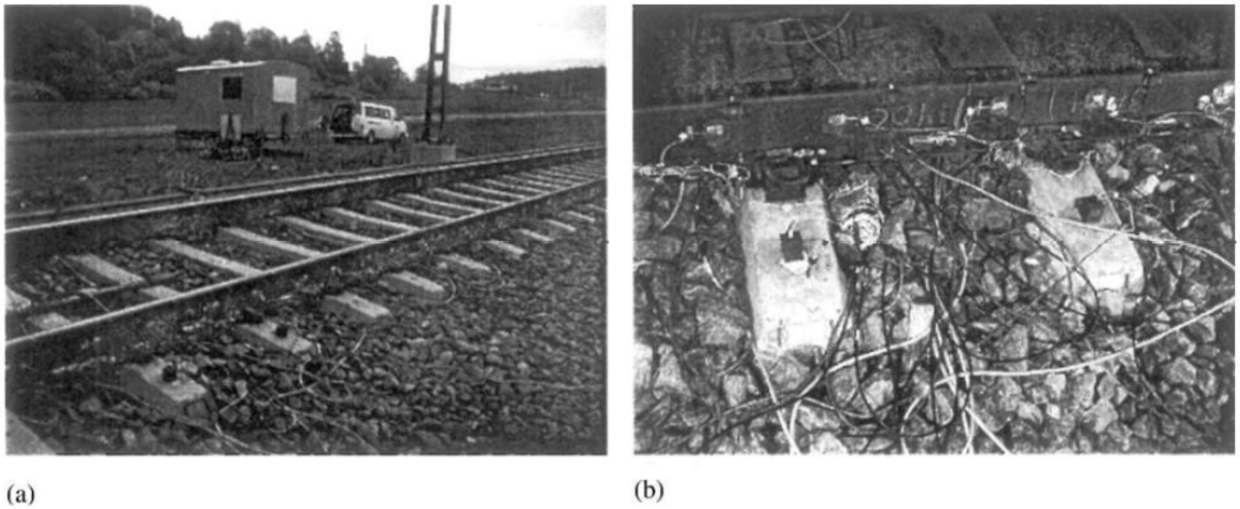
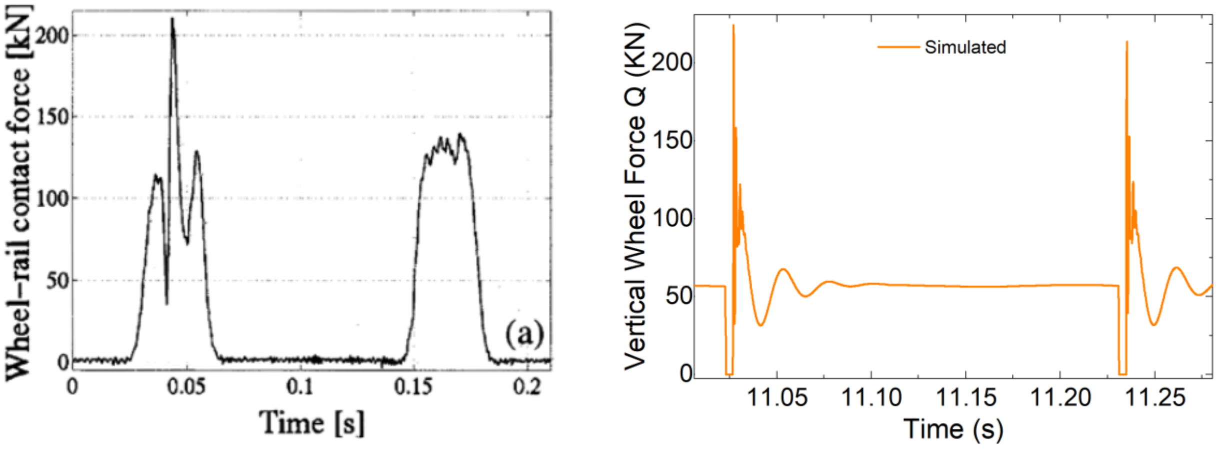


Figure 42: Photographs from the test site on Svealandsbanan (2000): (a) instrumented track and the wagon with computer equipment for collection of signals from the instrumented track; (b) instrumentation on rails and sleepers, including strain gauges on the rail web, rail foot and sleepers, and accelerometers underneath the railhead and on top of the sleepers [23].

Analysis was done on wheel-rail Impact force based on the retrieved real testing data and simulation results of the Simpack MBD model of EDR low-speed vehicle with the same parameters, and the following findings were made.

It can be observed in figure 43 that the test result of vertical Impact force is relatively close to the simulated result while the vehicle moves at 50 km/hr witha 100mm wheel flat. For instance, the peak value of the simulated result Figure 43 a) is 211 kN, while the measured result Figure 43 b) is 224 kN m/s², with just a 5.8% relative difference between the two values.



a) b)

Figure 43: Time history of the vertical wheel-rail contact force with100 mm wheelflat & at a train speed of 50 km/h. (a) measured by wheel impact load detector [23] ; (b) Simulated on Simpack MBD model of EDR low-speed vehicle

Based on the comparison of the simulation and actual tests for wheel-rail Impact force the relative variation between the two results is 5.8%, proving that the MBS model simulated in this paper is reasonably close to the test vehicle.

Chapter 5 - Conclusion, Recommendations and Future work

5.1 Conclusion and Recommendations

A typical low-speed model of an EDR passenger coach built using SIMPACK integrated with MATLAB to estimate the wheel flat size and the rate of change of nominal radius due to the specific flat length. As stated above, the goal of the research was to study the influence of wheel flat for low-speed Train performance. The effects of wheel flat on the EDR Train Performance were then investigated using analyses considering various wheel flat lengths and low-speed ranges.

According to the results, the rail vehicle’s dynamic performances, including impact load, acceleration, amplitude, power spectrum density (PSD), and comfort level or ride index, are influenced mainly by wheel flat size, running speed, and track irregularity.

The analysis also shows that, the vertical wheel impact force exceeds the Warning limit and causes a moderate operating condition for a vehicle traveling at a speed of 60 km/hr with all of the investigated wheel flat lengths, and up to 75 and 55mm flat lengths at speeds of 70 and 80 km/hr respectively. For running speed of 70 and 80km/hr with a wheel flat length above 75mm and 55mm respectively and also for running speed of 90km/hr and 100km/hr with a wheel flat length above 45mm, vertical wheel impact force exceeds Alarm limit, implies that severe operating condition.

In general, Wheel-rail impact force rises with train speed for slower train speeds as shown in figure 33. Yet, at higher speeds, the wheel-rail impact force reaches a maximum value at a certain speed and then decreases significantly. This is because after this speed, there is less impact or effect when a flat comes into contact with a rail at a sufficiently fast speed. This is caused by wheel flying or wheel rail contact loss. The size of the wheel flat and irregularity of the track directly influenced impact load, Vertical acceleration, and Ride Index. Therefore, the result shows that as the wheel flat, vehicle speed , and track excitation increase the overall train performance, safety, reliability and comfort highly influenced. Running speed causes typically an increase in vertical acceleration, along with its amplitude and power spectrum density (PSD), which reaches a maximum value at a specific speed of 70km/hr before beginning to decline sharply.

As mentioned above, wheel flat typically had a significant impact on the dynamic performance of EDR passenger coaches, causing severe impact loads on both the vehicle and the track components, leading to damage and high maintenance costs, producing excessive vibration that reduces passenger comfort, significantly increases obnoxious noise, and impairs operational safety.

5.2 Recommendations

Due to the inherent characteristics of the capacity of a railway system, the failure-driven capacity-limiting events within a railway network should be kept to a minimum. This can be achieved by the use of appropriate existing and new condition monitoring systems, which can detect and predict failure events at an early stage such as installation of antiskid device which increases friction, and thereby reduce the posssiblity of skid and system like wayside inspection for detection of damaged wheels and wheel/rail impacts. For moderate operating condition of EDR vehicles identified by this study, re-profile of the damaged wheel may be used to reduce the influences and for severe operating condition of EDR vehicles identified by this study such as running at a speed of 70km/hr and 80km/hr with a wheel flat length above 75mm and 55mm respectively and also running at a speed of 90km/hr and 100km/hr with a wheel flat length above 45mm, replacement is needed since the cost of vehicle and track components maintenance due to operation with a defective wheel exceeds the cost of replacement of the defective wheel. And Maintaining the wheels in good condition and minimizing the number of wheel defects are important to prevent accelerated deterioration of the infrastructure, which decreases the asset's life [7].

5.3 Future work

Further research can be performed in order to analyze and validate the influence of wheel flat on EDR Trains, such as by improving the simulation model to accurately represent the vehicle flexibility and the wheelset in the simulation is assumed as a rigid body discounting the influence of flexible structure. To confirm the results with the real influences, analytical methods, experimental measurement, or a field test would be used in addition to simulation. Besides comfort, damage to the track and components of rail vehicles with its maintenance would be studied.

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Appendices

Appendix – 1: Matlab Code for Wheel flat Analysis

```
%standard wheel profile
%to check change of nominal radius due to wheel flat defect
R = 0.46; % Wheel nominal Radius
mm = 1000;
th_2 = 0:2*pi/mm:2*pi;  % radian of the wheelset
thhh_2 = th_2';
th_22 = th_2';
rad_rad = th_2*pi/180;
rad = -2*pi:2*pi/250:2*pi;
radd = rad';
ra_11 = 0:pi/2571428571/36:pi/2571428571;
ra_111 = ra_11';
x2 = R*cos(th_2);
y2 = R*sin(th_2);
R_actual = sqrt(x2.^2 + y2.^2);
RR_actual = R_actual';
%
% wheel flat

Lf = 0.040; % Length of wheel Flat
jj = 500; % Number of Discretization of flat
bb_ang = Lf/R;
zzz = jj*bb_ang/pi;
xf = 0:Lf/zzz:Lf; % Discretization function of specific wheel flat
xf_new = xf';
Df = Lf.^2/(16*R); % Equation of Change of nominal radius

% general equation

r_new = 0.5*Df*(1-cos(2*pi*xf/Lf)); %  Equation of wheelflat function
rr_new = r_new';
R_new = R+r_new;
delta_RRRR = R-R_new;
Rinv = delta_RRRR';
```