POLITECNICO DI MILANO

SCHOOL OF INDUSTRIAL AND INFORMATION ENGINEERING

Master of Science in Mechanical Engineering

HOW TO TUNE INDIAN RAILWAY NORMATIVE IN ORDER TO TEST COMPONENTS OF HIGH-SPEED INTEGRATED SYSTEM

Supervisor: Prof. Claudio Somaschini

Co-supervisor : Fabio Piccioli

Degree Thesis:

Abhisheik Ravichandran

877997

Academic Year 2018/19

Preface

This thesis is a part of my MSc in Mechanical Engineering at Politecnico di Milano and was carried out in collaboration with Italcertifer SpA group Ferrovie della stato Italiane in Florence, Italy.

I would like to thank my supervisor and examiner at Politecnico di Milano, Prof. Claudio Somaschini and my tutor Ing. Fabio Piccioli and co-supervisor Mr. Roberto Catini at Italcertifer SpA for their valuable support and assistance during the work.

I would also like to thank Prof. Stefano Bruni and Dr. Bin bin Liu for his help during my training period for the usage of software.

Abhisheik Ravichandran

Italy, 2019

Abstract

TITLE – HOW TO TUNE INDIAN RAILWAY NORMATIVE IN ORDER TO TEST ANY COMPONENTS OF HIGH-SPEED INTEGRATED SYSTEM

KEYWORDS :- Testing and simulation, Running behavior, EN14363:2005 & UIC 518 Standards , Train 18 , Indian norms and procedure, vehicle dynamics interaction with track

To study the comparative analysis on procedure of EN14363 standard benefiting over Indian railway testing standards on running behavior of semi high speed train. Choosing a new technology vehicle Train18 respecting Indian conditions to verify simulation (Software - Simpack) tests on running dynamics. The trains were modelled in Simpack using its technical parameters and characteristics of wheelset , bogie , car body. The track layout structure (broad gauge 1676mm) designed following Indian conditions with rail inclination of 1:20. The simulation tests are carried out in four different zones in dry test conditions in which operating speed and cant deficiency act as an influencing factor same as the procedure carried out by on-track tests respecting EN standards. Finally, to check the assessment quantities (Running safety, Track loading, Vibration behavior) falls within the limit values of EN standard to compare with the results of Indian testing standards.

Simulations were done with focus kept on results reaching below the limit values of running safety, track loading, and ride characteristics parameters. Since it is a new technology vehicle only normal measuring methods were taken from EN14363 Standard.

The results of these latter simulations showed that the vehicle would pass an authority approval process in its current configuration (designed for very safe conditions)

The vehicle ride behavior results show a very low acceleration values for both lateral and vertical displacements of car-body due to high damping values.

Contents

List of Figures

List of Tables

Chapter 1

Introduction

In this chapter the background and definition of the problem handled in the thesis are explained. The main purpose and delimitations of the work as well as the methodology are also explained.

1.1 Background :-

The company Integral coach factory (ICF) Chennai, India has developed a new technology vehicle called **TRAIN 18**, which is a semi high speed train (Electric Multiple Unit). For a new rail vehicle to be approved for running, a number of requirements needs to be fulfilled, a part of these would be vehicle's dynamic interaction with track. These quantities looked for mainly vertical and lateral acceleration in the vehicle and wheel rail forces and these can be obtained with simulations using a mathematical model of the vehicle. The model has to be verified with the procedure of on-track tests and then the simulation can be used for approval of the vehicle.

1.2 Problem Definition :-

The problem handled in the thesis can be summarized as: create and verify simulation model of the vehicle T18 and use that to see if the vehicle meets the requirements of running dynamics with **EN14363 STANDARD** respecting Indian conditions, parameters and relevance.

1.3 Purpose :-

The purpose of the work was to examine the running characteristics and behavior of T18 vehicle using a simulation model following EN14363 test procedures and see if it meets the limit values for approval and made a comparative analysis on how EN14363 standard testing on running behavior would benefit Indian vehicle on testing.

1.4 Methodology :-

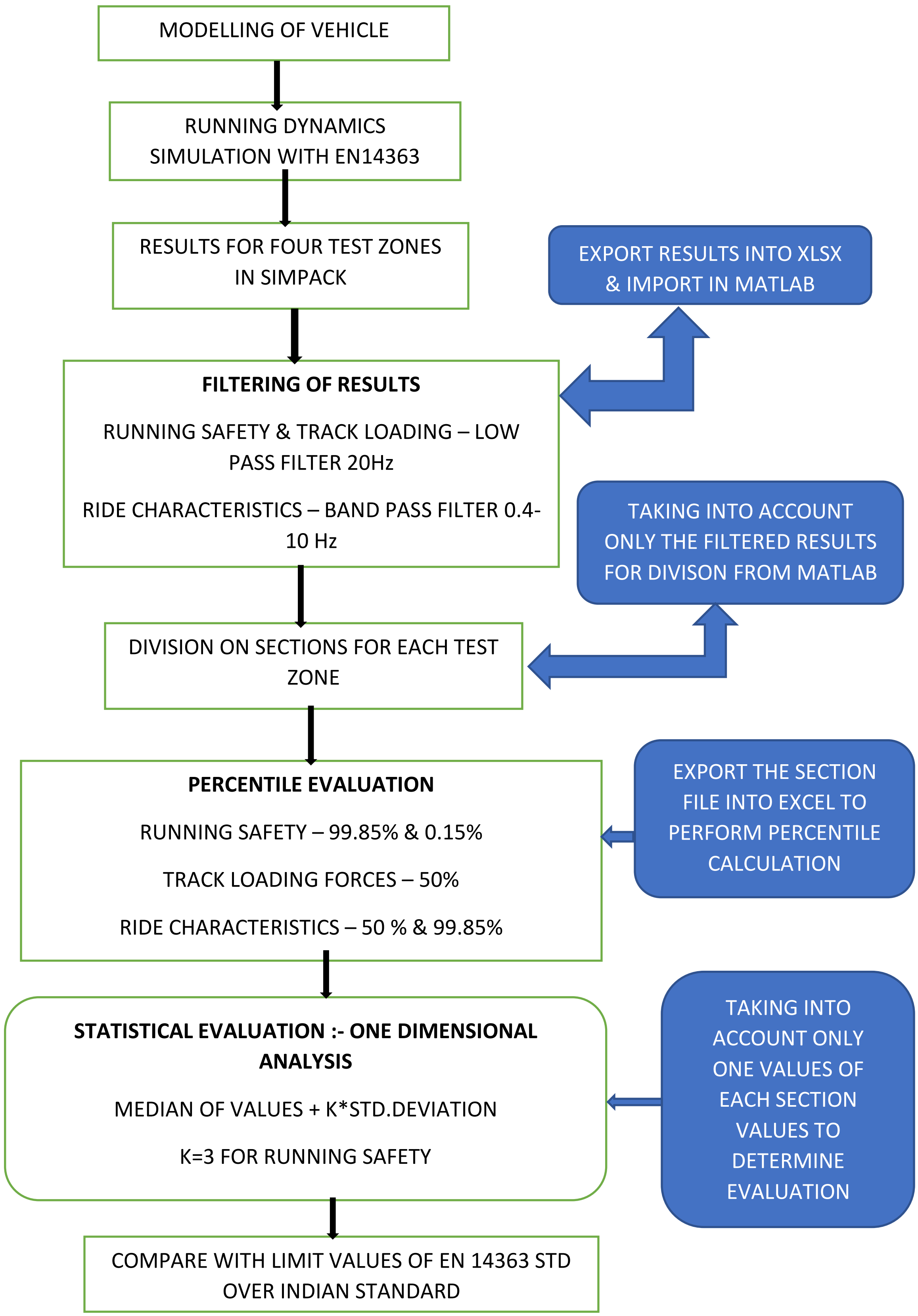
The vehicle model was created in the simulation software SIMPACK using required train data from documentation of RDSO and other references.

Then simulations were performed with vehicle speed, track geometry and data processing methods according to EN14363. The results were then analyzed to see if they were below their respective limit values. After the simulation model, comparing the results on **Running safety, Track loading, Vibration behavior** (Ride Quality) over Indian Railway norms.

1.5 Delimitations :-

To keep the work to level only with On-track test procedures, a few delimitations were done. Topics not covered in thesis:

a) Stationary tests
b) Partial or dispensation on-track test with simplified measuring method.


MODELLING OF VEHICLE
RUNNING DYNAMICS SIMULATION WITH EN14363
RESULTS FOR FOUR TEST ZONES IN SIMPACK
EXPORT RESULTS INTO XLSX & IMPORT IN MATLAB
FILTERING OF RESULTS
RUNNING SAFETY & TRACK LOADING – LOW PASS FILTER 20Hz
RIDE CHARACTERISTICS – BAND PASS FILTER 0.4-10 Hz
TAKING INTO ACCOUNT ONLY THE FILTERED RESULTS FOR DIVISON FROM MATLAB
DIVISION ON SECTIONS FOR EACH TEST ZONE
PERCENTILE EVALUATION
RUNNING SAFETY – 99.85% & 0.15%
TRACK LOADING FORCES – 50%
RIDE CHARACTERISTICS – 50 % & 99.85%
EXPORT THE SECTION FILE INTO EXCEL TO PERFORM PERCENTILE CALCULATION
STATISTICAL EVALUATION :- ONE DIMENSIONAL ANALYSIS
MEDIAN OF VALUES + K*STD.DEVIATION
K=3 FOR RUNNING SAFETY
TAKING INTO ACCOUNT ONLY ONE VALUES OF EACH SECTION VALUES TO DETERMINE EVALUATION
COMPARE WITH LIMIT VALUES OF EN 14363 STD OVER INDIAN STANDARD

Chapter 2

Frame of Reference

2.1 Requirements :-

The requirements for running safety for the vehicle type handled in the thesis are found in EN14363 and UIC-518.

2.1.1 EN14363 :-

This standard contains information on the vehicle running test needs to be performed, the assessment quantities with their limit values. The testing is divided into two parts: stationary test and on-track test. In the thesis the focus is on the tests explained in the on-track test section of the standard.

2.1.2 UIC-518 :-

This standard cover information on all provisions dealing with on-line running test and the analysis of the results in terms of rolling stock approval from point of view of dynamic behavior in connection with safety, track fatigue, running behavior. This also contains a code of practice with respect to track alignment design, track geometry and other operating conditions (speed and cant deficiency) to be complied with for the vehicle approval tests.

2.1.3 ERA/TD/2012-17/INT :-

This document provides the necessary additional specifications to perform running dynamic behavior testing of rolling stock. The method of tests and track geometric quality for the running behavior testing are outlined for accessing a rolling stock running dynamic under TSI (Technical Specifications for Interoperability)

1	EN 14363:2005	Railway applications - Testing for the acceptance of running characteristics of railway vehicles
2	UIC-518	Testing and approval of railway vehicles from the point of view of dynamic behavior – Safety , Track fatigue , Running behavior

3	ERA/TD/2012-17/INT	Running dynamics – Applications of EN14363:2005
4	EN 15663:2009	Railway applications – Definition of vehicle reference masses

2.2 Assessment values :-

As a first step, it had to be decided if a complete or just a partial on-track test was needed. Since the test was being performed for an initial acceptance of the vehicle, the complete on-track test was needed. Following this, a measurement method shall be determined with the choices being normal and simplified measuring method, the simplified method differs from normal method is that no wheel-rail forces are measured. The measuring method is determined using the flow chart and for the studied vehicle it came to know if it was deemed new technology vehicle or not. The quantities that needed to be measured with normal measuring method can be seen [1].

Here Y and Q are the track forces meaning they are resultant forces in the contact between wheel and rail. Y is the lateral guiding force and Q is the vertical force.

ASSESSMENT VALUES	SYMBOL	NORMAL MEASURING METHOD
RUNNING SAFETY	$\sum Y_{MAX}$ $(Y/Q)_{MAX}$ $\sum Y_{RMS}$	Maximum sum of guiding force Maximum quotient of guiding force over wheel force Moving rms of guiding force
TRACK LOADING	Y_{QST} Q_{QST} Q_{MAX}	Quasi-static guiding force Wheel force Maximum wheel force
VIBRATION BEHAVIOR	$\ddot{y}^*_{QST}$ $\ddot{y}^*_{MAX}$, z^*_{MAX} $\ddot{y}^*_{RMS}$, z^*_{RMS}	Quasi-static acceleration in vehicle body Maximum acceleration in vehicle body Rms of acceleration in vehicle body

Table.1. Normal measuring methods

The acceleration in the vehicle body are normally measured above each bogie and as well as in the longitudinal center of the body for non-articulated type bogies. These positions were chosen because this is where the response generally would be the highest and also these positions would be measured following the standard.

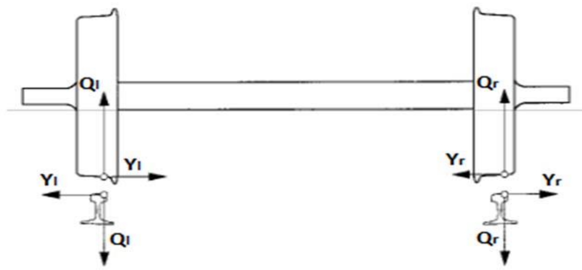


Fig.2.1 Wheel-rail contact

2.3 Test Conditions :-

Testing of the vehicle needed to be carried out in four different test zones. The first test zone is straight track and curves with very large curve radius. In this particular zone the testing of the vehicle is carried out in the area of vehicle's permissible speed. The second test zone is in the large curve radii. Here the testing of the vehicle is carried out in vehicle's permissible speed and with high cant deficiency. The third zone is in the small curve radius between 400 m and 600 m. the fourth zone is in very small curve radii between 250 m and 400 m. The testing of the vehicle for zones 3 and 4 are carried out in the area of vehicle's permissible cant deficiency [2].

The following table shows the test conditions for track sections in straight track and very large curves

TEST CHARACTERISTICS	**TEST ZONE 1 (Straight track & very large curves)**
Length of track section L_{ts} $V \leq 220$ km/h	250 m
Minimal number of track sections $n_{ts,min}$	25
Minimal length of the sum of all track sections $\sum L_{ts}$	10 km

Table.2 Test conditions test zones

The following table shows the test conditions for track sections in curves

TEST CHARACTERISTICS	**TEST ZONE**		
		3 **400 m ≤ R < 600 m**	**4** **250 m ≤ R < 400 m**
Length of track section L_{ts}		100 m	70 m
$V \leq 140$ km/h 140 km/h < $V \leq 220$ km/h	100 m 250 m		
Minimal number of track sections $n_{ts,min}$	25	50	25
Minimal total length of track sections $\sum L_{ts}$	10 km		
Mean value of curve radius of all track sections R_{mwa}		500 m ±50 m	300 m +50 m, -20 m

2.4 Test Zones:-

'On-track' tests for the testing of running characteristics are carried out in four different test zones. In each test zone, the test condition for track and operation differ with regard to the ranges of values to be examined for track layout, speed and cant deficiency [1].

TEST ZONE	**OBJECTIVE**	**ANTICIPATED VEHICLE CHARACTERISTICS**
1. Straight track and curves with very large radii	Testing of the vehicle in the area of the vehicles permissible speed	There are no or only small quasi-static guiding forces or accelerations, but larger dynamic content in all evaluation variables
2. Large radius	Testing of the vehicle in	Superposition of quasi-static

curves	the area of the vehicles permissible speed and high cant deficiency	and dynamic contents of all evaluation variables
3. Small radius curves 400 m ≤R≤ 600m	Testing of the vehicle in the area of the vehicles permissible cant deficiency	Larger quasi-static guiding forces, wheel forces and accelerations, dynamic content generally decreases
4. Very small radius curves 250 m ≤ R ≤ 400 m	Testing of the vehicle in the area of the vehicles permissible cant deficiency	Larger quasi-static guiding forces, wheel forces and accelerations, dynamic content generally decreases

Table.3. Objectives of test zone with influencing parameters

The speed and cant deficiency for different test zone can be seen in the following table. Cant deficiency- The missing amount of outer rail super elevation required to cancel the centrifugal acceleration component above the rail level during the running of rolling stock I curves. For test zone 1 and 2, the vehicle speed shall be specified as test parameter. The relevant speed is the desired permissible maximum speed of vehicle V_{adm}. The vehicle desired maximum cant deficiency is denoted as cd_{adm} [2].

TEST ZONES	SPEED, V	CANT DEFICIENCY, cd	TOLERANCE
1	$V = \max(1.1*V_{adm}, V_{adm}+10$ km/h)	Cd ≤ 40 mm	± 5 km/h
2	$V_{adm} \le V \le 1.1*V_{adm}$	$0.75*cd_{adm} \le cd \le 1.1*cd_{adm}$	± 5 km/h $\pm 0.05*cd_{adm}$
3	$V \le 1.1*V_{adm}$	$0.75*cd_{adm} \le cd \le 1.1*cd_{adm}$	$\pm 0.05*cd_{adm}$
4	$V \le 1.1*V_{adm}$	$0.75*cd_{adm} \le cd \le 1.1*cd_{adm}$	$\pm 0.05*cd_{adm}$

Table.4. Test zones speed & cant deficiency limits

2.5 Processing :-

The processing of measured signals differs between the different quantities (Running safety, ride quality and track loading). The filtering unit for different quantities can be seen in the following table [1].

Assessment value	**Filtering for evaluation**	**Method of classification**	**Characteristics values**	**Grouping & conversion**	
				Test zone 1	**Test zone 2,3,4**
TRACK LOADING					
Guiding force Y_{qst} wheelset 1,2	Low pass filter 20 Hz	Random sampling method	h_o = 50 %	Per bogie group all wheels	Per wheelset group external wheels
Wheel force Q_{qst} wheels 11,12,21,22	Low pass filter 20 Hz	Random sampling method	h_o = 50 %		Per bogie group external wheels
Wheel force Q_{max} wheels 11,12,21,22	Low pass filter 20 Hz	Random sampling method	h_2 = 99.85 %		Per bogie group external wheels

RUNNING SAFETY Sum of guiding forces $\sum Y_{max}$ wheelset 1, 2 Quotient Y/Q leading wheelset	Low pass filter 20 Hz Low pass filter 20 Hz	Sliding mean method with window length 2 m and step length 5 m Sliding mean method with window length 2 m and step length 5 m	h_1 = 0.15 % h_2 = 99.85 % h_1 = 0.15 % h_2 = 99.85 %	Per wheelset group	Per wheelset group For leading wheelset group external wheels
RIDE QUALITY Acceleration in vehicle body $\ddot{y}^{*}_{qst}$ Acceleration in vehicle body $\ddot{y}^{*}_{max}$ & z^{*}_{max} Acceleration in vehicle body $\ddot{y}^{*}_{rms}$ & z^{*}_{rms}	Low pass filter 20 Hz Band pass filter 0.4 to 10 Hz Band pass filter 0.4 to 10 Hz	Random sampling method Random sampling method Random sampling method	h_o = 50 % h_1 = 0.15 % h_2 = 99.85 %	Per end group	Per end group of external wheels Per end group
INFLUENCING PARAMETERS Speed V Cant deficiency cd	Low pass filter 4 Hz Low pass filter 4 Hz	Random sampling method Random sampling method	h_o = 50 % h_o = 50 %		

Table.5. Measuring processing parameters

2.6 Limit values :-

There are different limit values with different significance with regard to safety issues; there are limits to each quantity. The limit values for ride characteristics are no running safety relevant limits but needs to consider with regard to vibration load on passengers, vehicle components. There are additional limit values for track loading (Combined rail loading quantity B_{qst} and rail surface damage quantity T_{qst}) to determine appropriate operating and vehicle conditions depending on track layout, track design, track quality [3].

The limit values for normal measuring method are to be applied

RUNNING SAFETY:

a) Sum of guiding forces $\sum Y_{MAX}$
   The safety critical limit for track shifting
   $\sum Y_{MAX,lim} = k1(\ 10+2Q_o/3)$ kN
   Factor k1= 1.0 (locomotives, multiple units, passenger coaches)

b) Quotient of guiding force and wheel force $(Y/Q)_{MAX}$
   The critical safety limit for the quotient of leading wheel
   $(Y/Q)_{MAX,LIM} = 0.8$ (Section for full curve)
   $(Y/Q)_{MAX,LIM} = 1.2$ (Section for transition regions)

TRACK LOADING:

a) Quasi-static guiding force Y_{qst} :-
   $Y_{qst,lim} = 60$ kN (Test zones 2,3,4 excluding transition sections)
b) Quasi-static wheel force Q_{qst}
   $Q_{qst,lim} = 145$ kN (Test zones 2,3,4 excluding transition section)
c) Maximum wheel force Q_{max} :-
   $Q_{max,lim} = 90 + Q_o$ kN

$V_{adm} \leq 160$ km/h: $Q_{max,lim} \leq 200$ kN

160/h $< V_{adm} \leq 200$ km/h: $Q_{max,lim} \leq 190$ kN

d) Combined rail loading quantity B_{qst} :-

$B_{qst} = Y_{qst} + 0.83\ Q_{qst}$

$B_{max} = (|Y| + 0.91\ Q)_{max}$

e) Rail surface damage quantity T_{qst} :-

A measure for controlling the wear of rails. The interaction between wear and surface initiated rolling contact fatigue is referred to as rail surface damage (RSD). The advantage is that it normalizes the influence of varying contact conditions and wheel/rail friction.

$$Tqst = \frac{Qqst}{10000} * (330.f^2 - 62.f + 4)$$

$$f = \frac{Yqst}{Qqst} + 0.62\frac{Tx,qst}{Qqst}$$

There are no limit values for both Rail surface damage and rail loading quantities.

RIDE CHARACTERISTICS:

a) Quasi-static accelerations in the vehicle body $\ddot{y}^*_{qst}$

b) Maximum accelerations in the vehicle body $\ddot{y}^*_{max}$, z^*_{max}

c) Root mean square of accelerations in vehicle body $\ddot{y}^*_{rms}$, z^*_{rms}

ASSESSMENT VEHICLE,TEST CONDITIONS	LIMIT VALUES FOR ACCELERATION IN VEHICLE BODY m/s²				
RIDE CHARACTERISTICS	$\ddot{y}^*_{qst}$	$\ddot{y}^*_{max}$	z^*_{max}	$\ddot{y}^*_{rms}$	z^*_{rms}
Locomotives , Power cars	1.5	2.5	2.5	0.5	1.0
Multiple units, Passenger coaches	1.5	2.5	2.5	0.5	0.75

Table.6. Limit values for ride characteristics

2.7 Vehicle Description :-

LHB TYPE COACH :-

LHB coach body type is designed and manufactured by ICF (INTEGRAL COACH FACTORY) for TRAIN 18 and bogies are designed by FIAT Switzerland. It can withstand operating speed of 160 kmph and maximum speed up to 200 kmph [11].

HOW IT BENEFITS RAILWAYS:

A Longer coach – 2 m longer than conventional type coach. This means more travel space, increased in seating capacity and wider bays and doorways.

A lighter coach – weight of LHB coach is 10 % lesser than conventional coaches. This means low haulage cost but also less wear and tear of coaches and tracks.

A higher speed coach – LHB coaches are designed to run at speeds even for 200 kmph when infrastructure satisfies the condition.

Lesser maintenance – Bogie with less moving parts used.

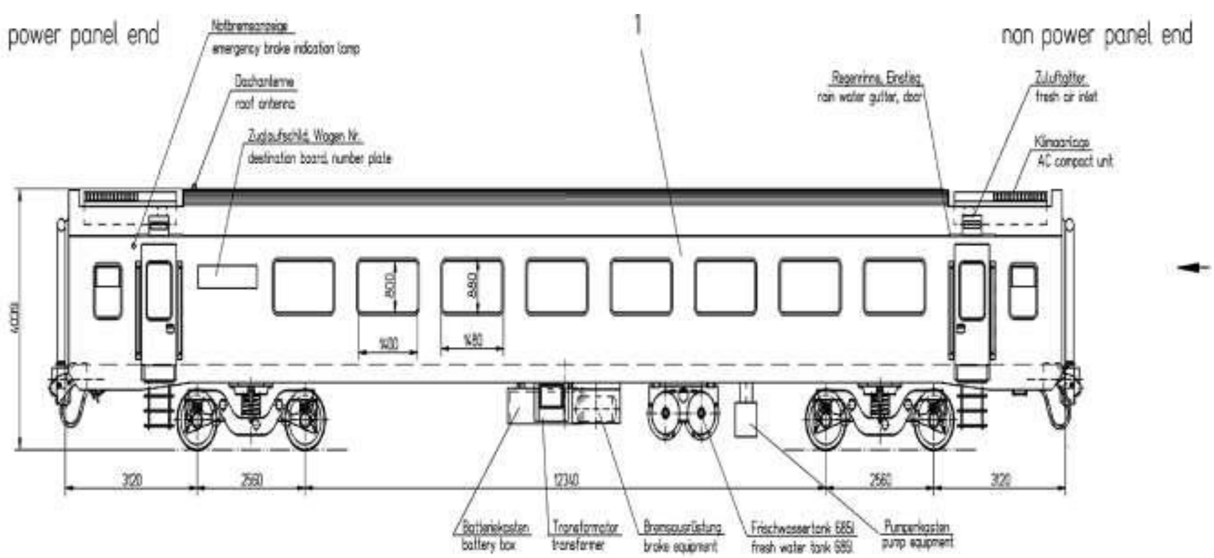


Fig.2.2 LHB Coach dimensions

DESIGN FEATURES OF LHB COACH SHELL:

Length over buffer	24000 mm
Length over head stock	23540 mm
Width	3030 mm
Height from rail level	4025 mm
Codal life	30 years
Maximum distance between inner wheels	12345 mm
Maximum tare weight	40.29 Tonne
No of passengers	78
Test speed	181 Kmph
Fit to run at speed of	160 Kmph
Axle load	17 tonne

Table 7. LHB coach characteristics

2.8 Simpack :-

Simpack is a general-purpose Multibody simulation (MBS) software used for dynamic analysis of any mechanical and mechatronic systems. It enables to generate and solve virtual 3D models in order to predict and visualize motion, coupling forces and stresses. Simpack is used for design and analysis of rail-based vehicle of articulated high-speed trains. With the vehicle model a track model is needed together with track design geometry and track irregularities. Using the model some different calculations can be made including the frequency analysis of vehicle and time simulations over a defined track. When performing time simulations, there are some different methods that solve ordinary differential equation. In simulation the software also uses hertz theory to calculate the contact patch and contact pressure between wheel and rail. This theory says that an elliptical contact arises if two bodies are pressed together with normal force. The software also uses Kalker's simplified theory of rolling contact to calculate the tangential forces in the contact. This is a frequently used model of wheel-rail contact since it often gives an exact description while being faster to use than the complete theory. From a simulation there is a lot of different output data available including displacements and accelerations at any position in all bodies, spring and damper displacement forces, wheel and rail forces, wheel and rail wear, derailment co-efficient [7].

2.9 Guide on Derailments :-

2.9.1 Derailments on Curves :-

The rolling stock has higher chances of derailing on a curved track since the flange is almost continuously pressing against the running edge of outer rail in addition to the normal tread contact with the rail [10].

Adverse factors on curves

- Excessive angular wear on the outer rail
- Excessive flattening of head on the inner rail
- Gauge widening
- Track distortion

2.9.2 Cant or Super-elevation :-

When a vehicle moves on a circular curve, it is subjected to a constant radial acceleration which produces a centrifugal force acting away from the centre in a radial direction. The value of this centrifugal force is given by the formula :

$$F = \frac{WV\text{^}2}{GR}$$

F – Centrifugal force

W – Weight of the vehicle

V – Speed of the vehicle

G – Acceleration due to gravity

R – Radius of curve section

To counter this centrifugal force, outer rail on the curves is kept little higher than the inner rail. The inner rail is normally maintained at its original level and considered as a reference rail. Raising of outer rail on curve to a specified height in this fashion is known as **Cant** or **Super-elevation**. The state of equilibrium reaches when both the wheels bear equally on the rails. In this state of equilibrium, the level difference between outer and inner rail on the curve is called **equilibrium super elevation**. The equilibrium super elevation is given by :

$$e = \frac{GV\hat{}2}{127\,R}$$

G – Gauge + width of rail head

R – Radius of curve

2.9.3 Reasons for providing super-elevation :-

- To have a better distribution of load on two rails
- To reduce wear and tear on rails
- To provide comfort to passengers
- To neutralize the effect on lateral force

2.9.4 Cant deficiency :-

Cant deficiency is the difference between **equilibrium cant** necessary for maximum permissible speed on a curve and the actual cant provided.
The cant deficiency is limited due to following two considerations :

- Higher cant deficiency causes discomfort to passengers.
- Higher cant deficiency leads to higher unbalanced centrifugal force which in turn requires stronger track and fastening to withstand higher lateral force.

As soon as a vehicle enters a circular curve from straight alignment, it is subjected to centrifugal forces. This increases lateral flange force and affects the track alignment. In order to limit these and provide smooth entry to the curve, transition curves are provided on either side of a circular curve . The change of degree is uniform throughout the length of transition curve. Thus, the curvature increases gradually from zero at the straight end and becomes equal to the curvature of circular portion at the other end. The super-elevation increases at the same rate as curvature so that full cant is achieved simultaneously with the beginning of circular arc. This gives gradual and slow building of centrifugal force as well as super-elevation. The transitions are thus critical portions to be examined for the correctness during derailments on curves. The transition curves are usually laid in the shape of a cubic parabola [4].

2.9.5 Length of transition curve :-

The length of transition portion depends upon the degree of curve, max. permissible speed, amount of super-elevation and the rate at which the cant is run off. The desirable length of transition curve in meters is maximum of following three values

(1) 0.008 Ca*Vm

(2) 0.008 Cd * Vm

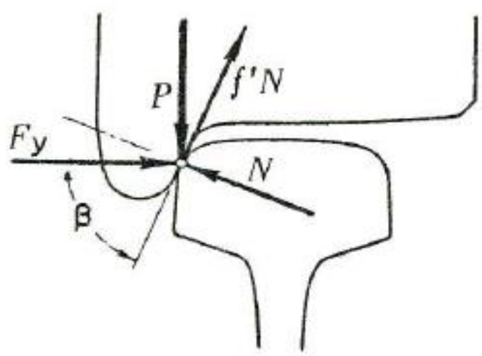
(3) 0.72 Ca

Where Ca is actual cant provided in mm, Cd is cant deficiency in mm and Vm is maximum permissible speed in kmph [4].

2.10 Indian norms and procedures :-

2.10.1 Derailment co-efficient :-

Nadal criterion :-



$$P \operatorname{sen} \beta = F_y \cos \beta + f' N$$

$$N = P \cos \beta + F_y \operatorname{sen} \beta$$

$$P \operatorname{sen}\beta - f' P \cos\beta = F_y \cos\beta + f' F_y \operatorname{sen}\beta$$

$$\boxed{\frac{F_y}{P} = \frac{\operatorname{tg}\beta - f'}{1 + f' \operatorname{tg}\beta} = \varphi(f', \beta)}$$

The first way to ensure safety is to give sufficient contact angle to the flange. The second preference is to reduce the lateral force Y by good design of bogie. Another option is to limit the track twist and diminution of Q forces. The last way to is to reduce the friction co-efficient by lubrication. In Europe, this is commonly carried out at wheel flange or on the gauge corner of the rail in curve sections. The friction forces are also limited in lateral direction by presence of a longitudinal forces. The friction co-efficient is shared between the two directions [5].

In the Pochet Nadal formula, this sharing effect is not considered, making the formula adequate for independent wheels. This means that a rigid wheelset, where the longitudinal forces are important on attack wheel, will be safer than an independent wheel in the same conditions.

2.10.2 Ride index :-

Testing on Rolling stock follows AAR and UIC – 518 standards to test the ride characteristics of the vehicle or carriages. Ride Index value for EMU trains are less than 4 (usually ranges from 3.25 – 3.75) [10].

Human sensation of comfort proportional to Displacement, Rate of change of Acceleration, Acceleration.

$$RI = 0.896\,(g(f)*b^3/f)^{0.1}$$

$$g(f) = kf^2$$

b = acceleration amplitude

g(f) = ride comfort correction factor

k = 0.325 for vertical ride Index (0.5 – 5.4 Hz)

k = 0.8 for lateral ride index (0.5 – 5.4 Hz)

Relation between passenger comfort and ride index

RIDE INDEX	APPRECIATION	FATIGUE LIMIT
1.0	Very good	Over 24 hours
1.5	Almost very good	Over 24 hours
2.0	Good	Over 24 hours
2.5	Neatly good	13 hours
3.0	Passable	5.6 hours
3.5	Still passable	2.8 hours
4.0	Able to run	1.5 hours
4.5	Not able to run	45 min

Chapter 3

Simulation Model :-

3.1 Vehicle Model :-

The model was built with four masses (rigid bodies): the car-body, bogie frame and the two wheelsets. To keep the model as simple as possible all masses were assumed to be rigid, see Fig.3.1

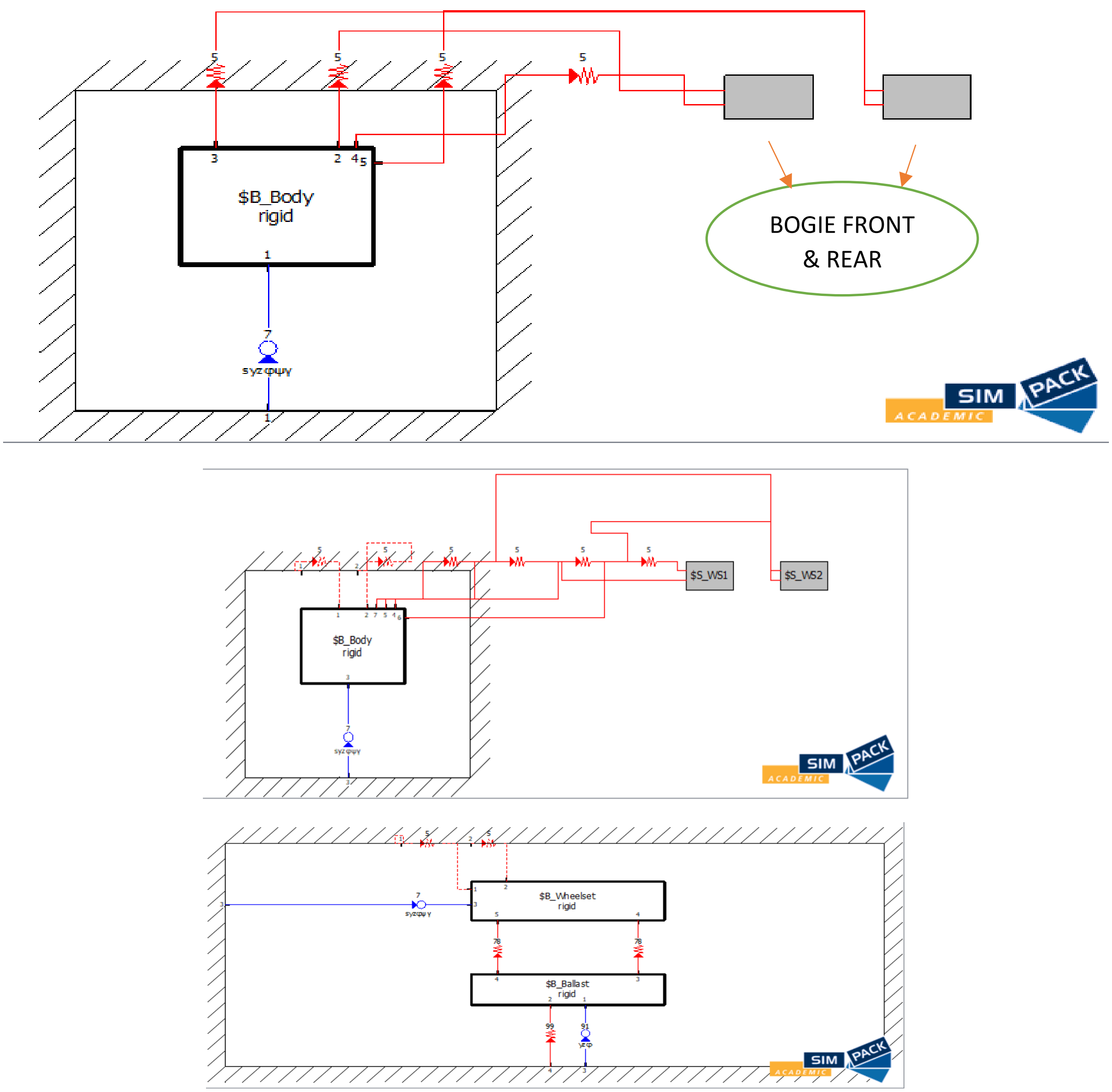
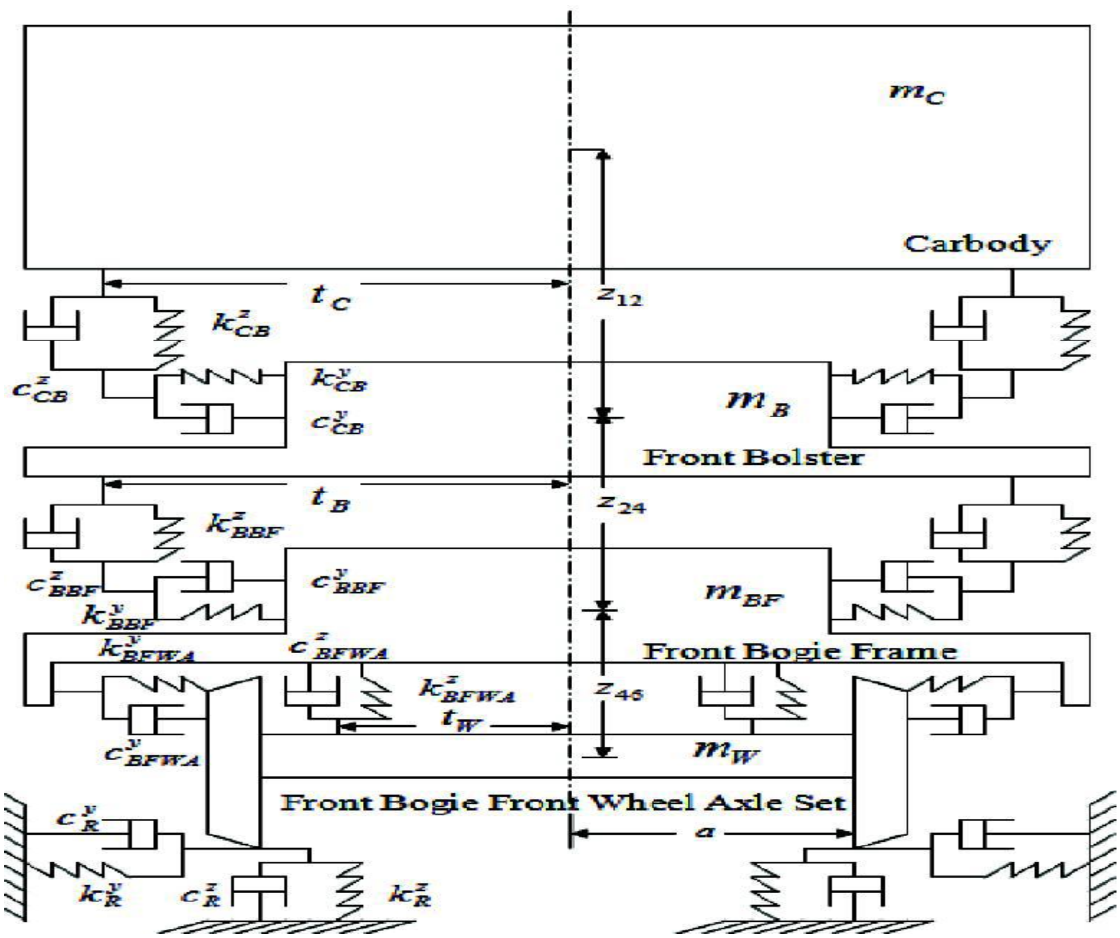


Fig.3.1 Vehicle model

3.1.1 Mathematical Vehicle Modelling :-

The railway vehicle comprises of a car-body supported by two bogies one at each end. Bolsters are the intermediate member between the car-body and each bogie frame and is connected to car-body through side bearings. The bogie frame supports the weight of the car-body through a secondary suspension located between the car-body and the bogie frame. In passenger vehicles, each bogie usually consists of two wheel-axle sets that are connected through the primary suspension to the bogie frame. In addition, the wheels are usually tapered or profiled to provide a self-centering action as the axle traverses the track. The inertial axes system is fixed with the track while the origins of the body fixed axes system are located at the center of mass of different rigid bodies e.g. Car-body, bolster, wheel axle etc [9].



3.1.1 Wheelset Model :-

The wheelset model was taken from the template model for rail wheelset from Simpack. Here, the design of wheelset and its properties are designed based on Indian running conditions. The type of track joint is TYPE-7 GENERAL RAIL TRACK JOINT (6 Degrees of freedom) 5 dof without pitch angle and 1 dof with only s.

S – Longitudinal position (along track centre)

y - Lateral position

z – vertical position

phi – Roll angle (around s)

psi – Yaw angle (around z)

gam – pitch or rolling angle (around y).

The lateral distance of the rail is defined by the track gauge.

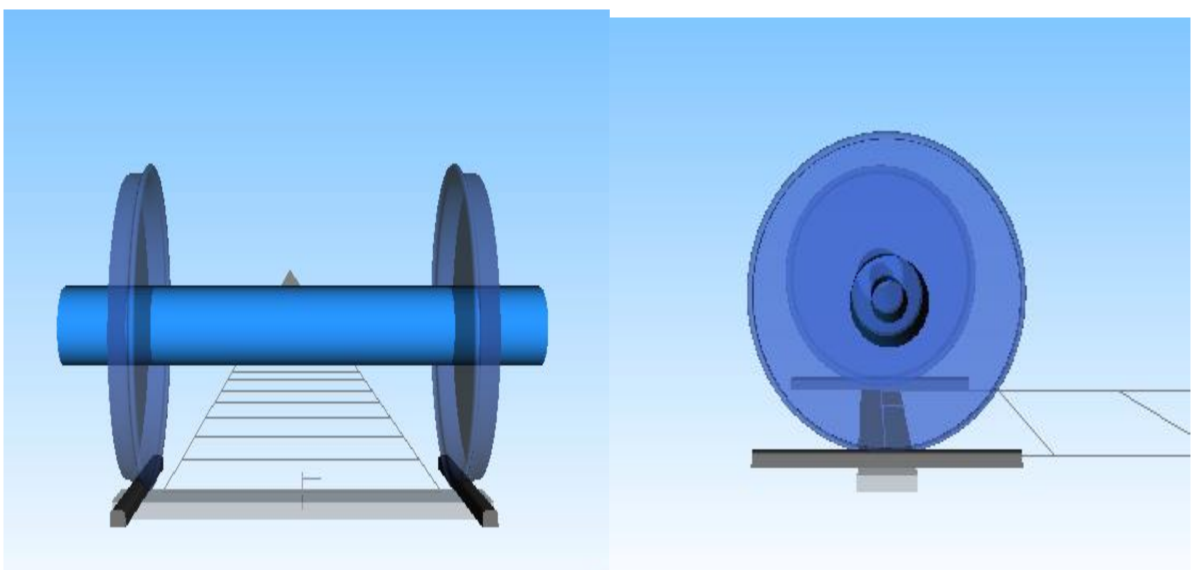


Fig.3.2 Wheelset Model

	INDIAN WHEELSET TYPE	ITALIAN WHEELSET TYPE
Axle length	2.56 m	2.2 m
Outer Diameter	0.24 m	0.18 m
Inner Diameter	0.11 m	0.08 m
Nominal Wheel Radius	0.46	0.46 m
Rail profile	UIC 60	UIC 60
Track gauge	1676 m	1435 m
Rail cant	1.20	1:40
Gauge measurement position	0.012 m	0.014 m
Wheel profile	S1002 TYPE	S1002 TYPE
Lateral wheel distance	0.8635 m	0.75 m
Friction co-efficient	0.3	0.4

Table.8 Wheelset geometry properties

Modal Check :-

Once the single wheelset model is finished by defining the geometrical properties of wheel and rail, we know that the model is not in equilibrium state, so depending upon the profile and the position there may be contact between the wheel and rail that exerts large contact forces.

Here, preload calculations were performed to bring the model to be in equilibrium state, by setting vehicle speed as zero to prevent the parasitic forces. The resulting preloads brings the half of wheelset weight force. The maximum residual acceleration has a very small number.

The model is checked by setting the vehicle global speed parameter by giving actual rail profile type and adjusting the solver settings for simulation time and sample rate for laid track distance[6].

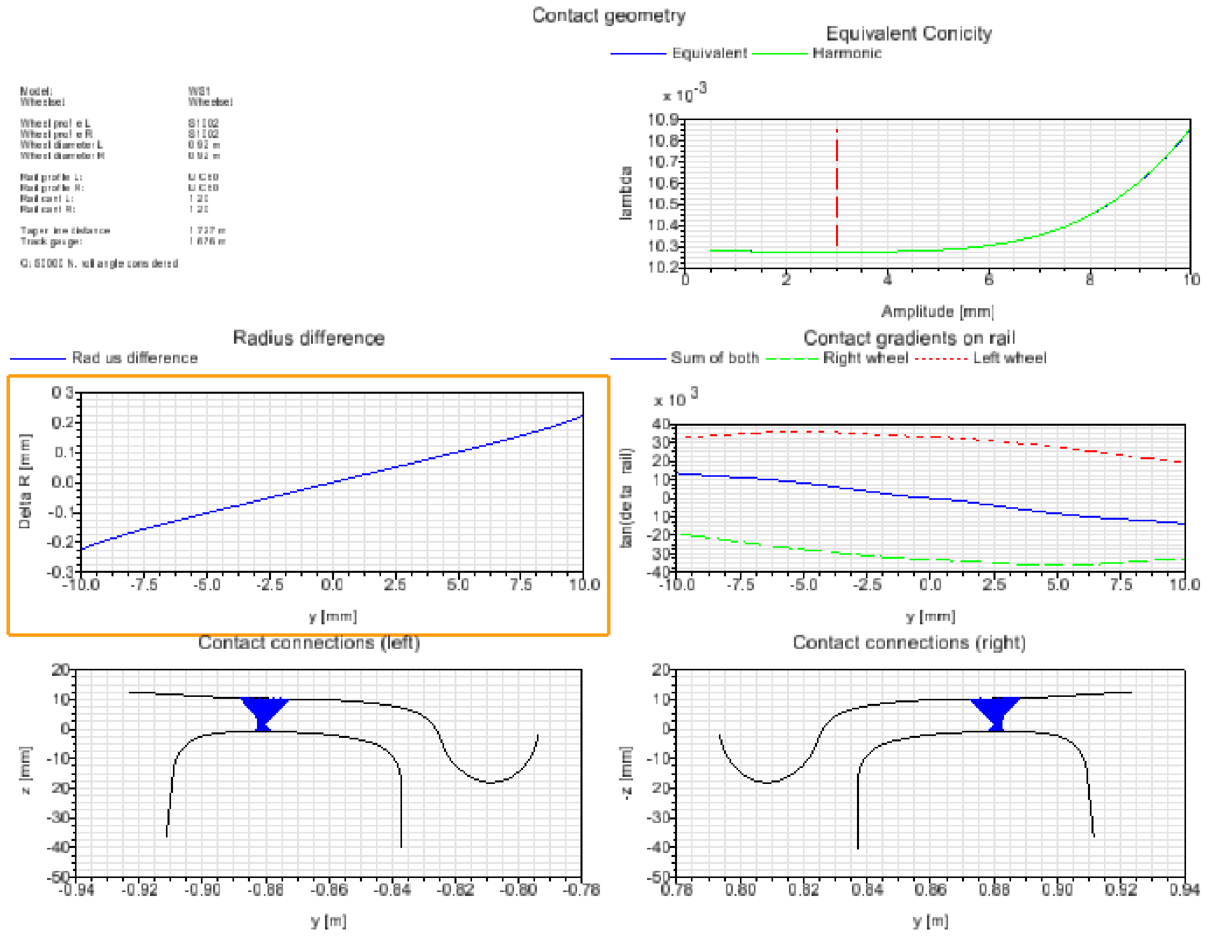


Fig.3.3 Contact geometry

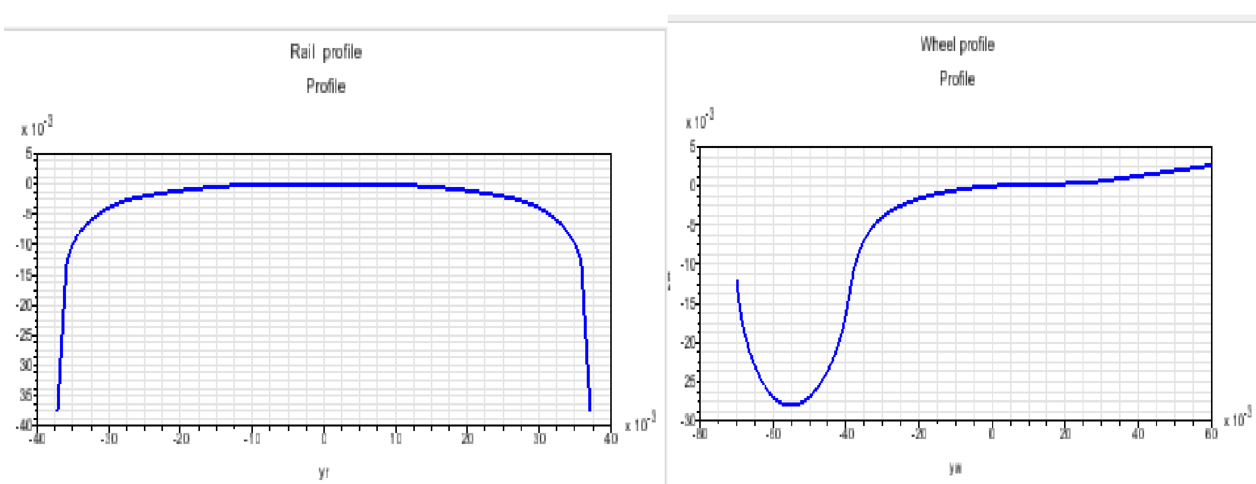


Fig.3.4 Wheel and Rail profile

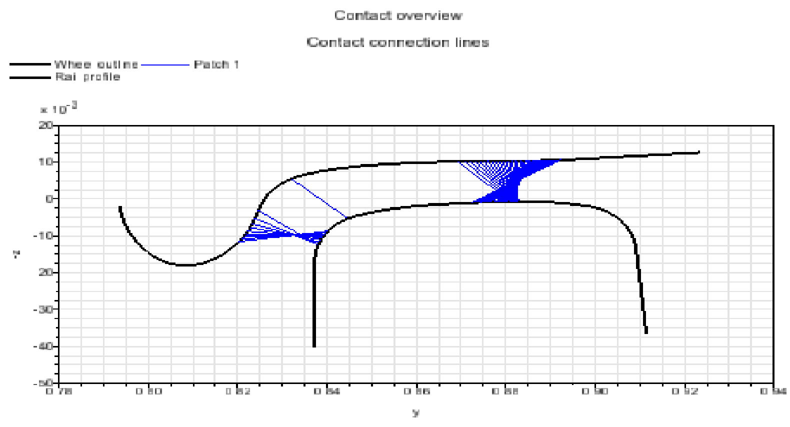


Fig.3.5 Contact overview

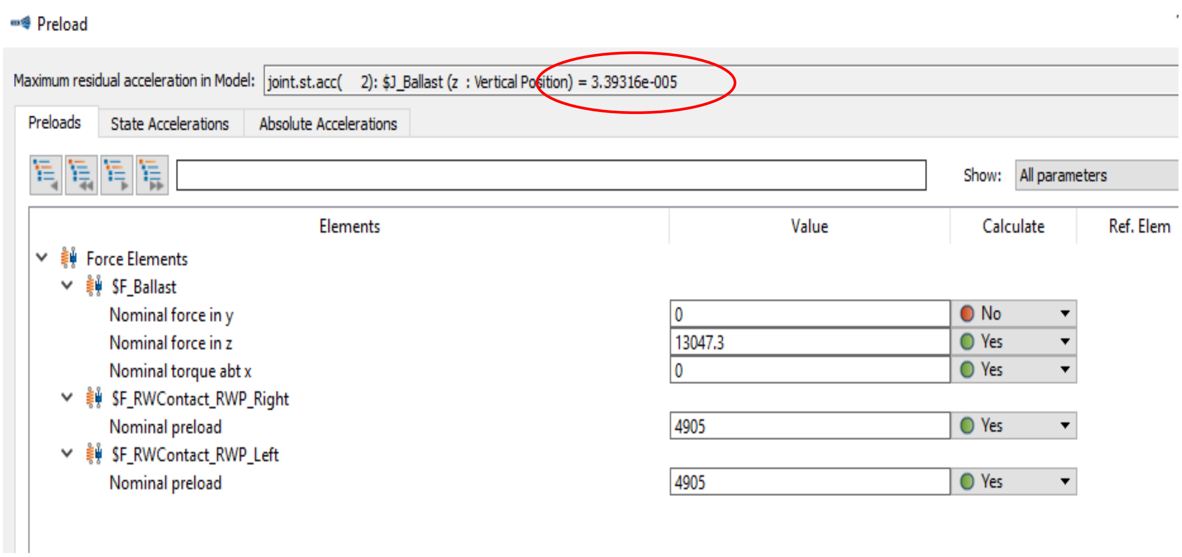


Fig.3.6 Preload results

3.1.2 Bogie Frame Model :-

A simple bogie model includes

- 2 Wheelsets
- 1 bogie frame
- Primary suspension system (4 spring-damper in parallel elements)

The new model was taken from the template model ‘Rail track’ (appears to be a rectangular box) and by defining the body type properties to bring out like the frame type (wheel rail bogie model). The primary suspensions are modelled with Spring and damper in parallel (Component ‘Cmp’ type force components are used). The mid frame connecting the two frames are aligned by changing the longitudinal position of the frame as the half of the length of wheelbase distance (2.5/2).

The wheelset model is loaded in the main bogie model, as both wheelsets are identical they can superimpose upon each other [8].

BOGIE BODY PROPERTIES	INDIAN BOGIE MODEL	ITALIAN BOGIE MODEL
Wheelbase	2.560 m	2.5 m
Mass of frame	3150 kg	3000 kg
Inertia I_{XX}	1713 kg m^2	1500 kg m^2
Inertia I_{YY}	3206 kg m^2	2500 Kg m^2
Inertia I_{ZZ}	4763 Kg m^2	2800 Kg m^2
Center of mass z	0.6 m	0.6 m
Frame length L1	3.534 m	3 m
Frame width	0.25 m	0.25 m
Frame height	0.6 m	0.6 m
Mid frame length in X	0.3 m	0.3 m
Mid frame length in Y	2.241 m	2 m
Frame length L2	1.6 m	1.2 m
Mid frame length in Z	0.2 m	0.2 m

Table.9 Comparison on bogie body properties

PRIMARY SUSPENSION PARAMETERS	INDIAN BOGIE MODEL TYPE	ITALIAN BOGIE MODEL TYPE
Stiffness k_X	3.e^7 N/m	3.e^7 N/m
Stiffness K_Y	4.e^6 N/m	4.e^6 N/m
Stiffness K_Z	1.2.e^6 N/m	1.2.e^6 N/m
Damping d_X	15000 Ns/m	15000 Ns/m
Damping d_Y	2000 Ns/m	2000 Ns/m
Damping d_Z	4000 Ns/m	4000 Ns/m

Table.10 Comparison on Primary suspension parameter

Process On Bogie Frame Model :-

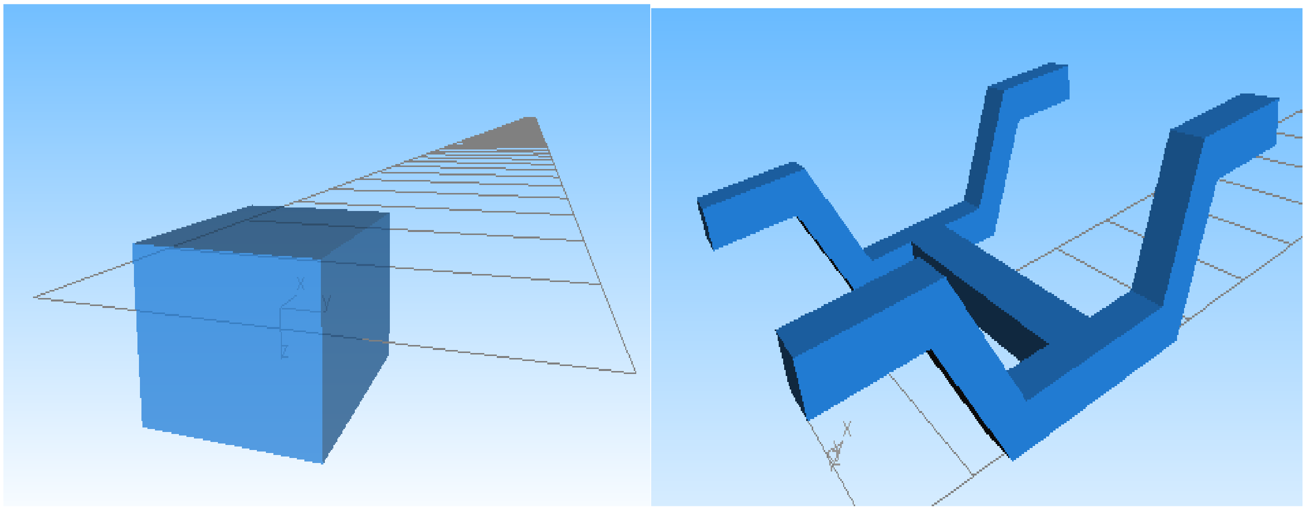


Fig.3.7 Bogie frame profile

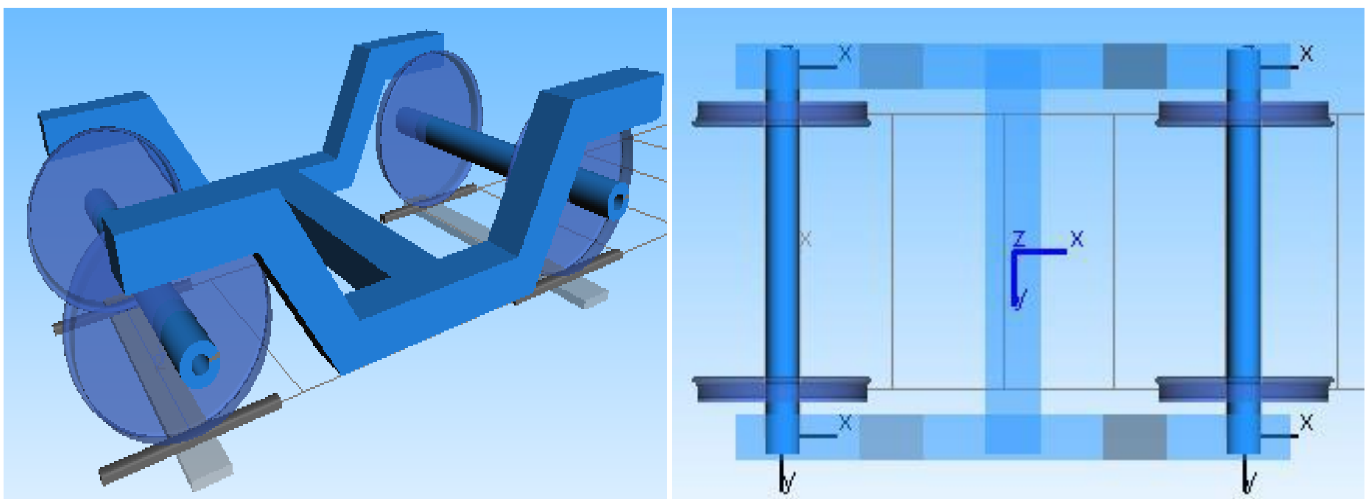


Fig.3.8 Wheelset arrangements and suspension positions

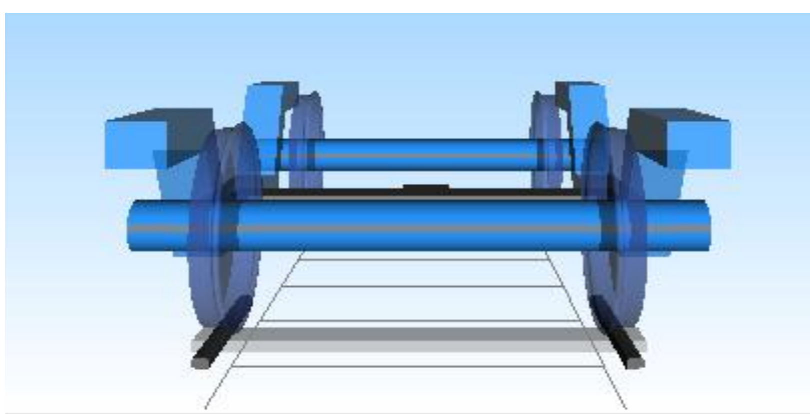


Fig.3.9 Bogie frame model with wheelset arrangements

Modal Check :- (Similar to wheelset model)

Here, preload calculations were performed to bring the model to be in equilibrium state, by setting vehicle speed as zero to prevent the parasitic forces. The resulting preloads brings the half of wheelset weight force. The maximum residual acceleration has a very small number.

The model is checked by setting the vehicle global speed parameter by giving actual rail profile type and adjusting the solver settings for simulation time and sample rate (100 Hz) for laid track distance [6].

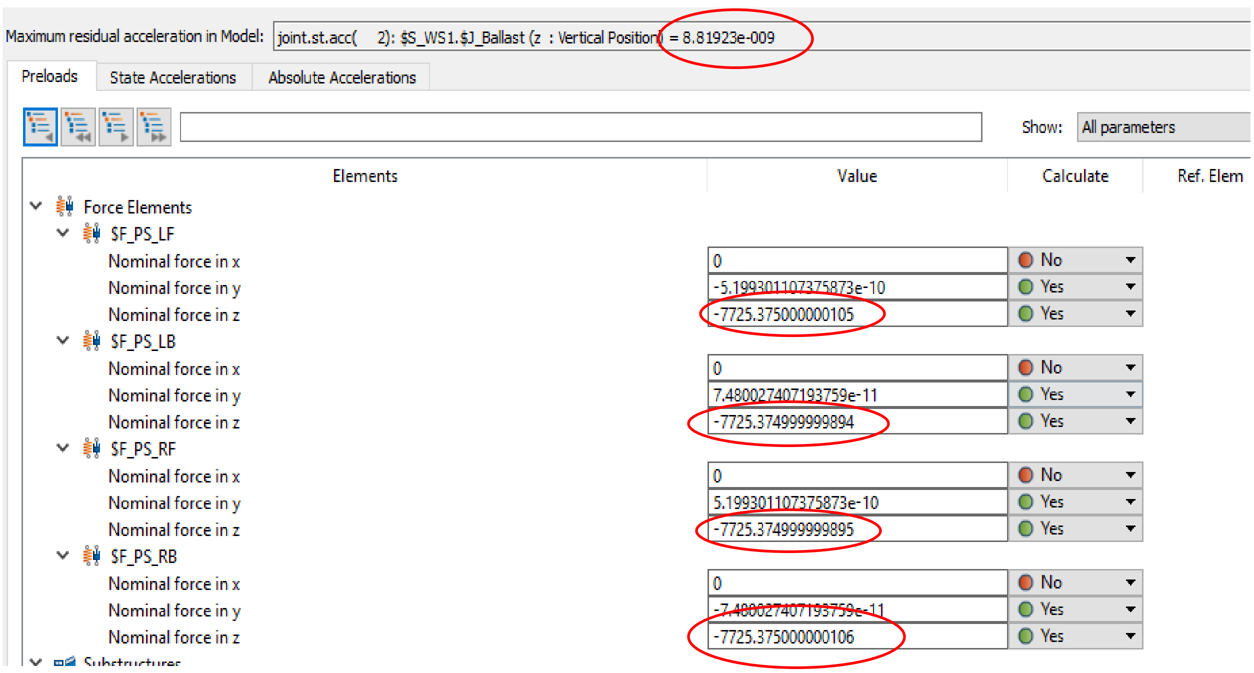


Fig.3.10 Preload for model check

3.1.3 Car Body Model :-

The BODY model was taken from the template model as 'Rail track' from Simpack. Here, the design of car-body and its properties are designed based on Indian cabin conditions (LHB type coaches). The car-body appears to be in a shape by selecting wheel rail cab and by defining the body properties based on LHB TYPE VEHICLE. Here centre of gravity is located above the body reference frame. By fixing the longitudinal position along the track from the starting surface set as zero, setting the markers for secondary suspension (Cmp force elements) and finally the body is ready to mount the bogies. First the two bogie models had overlapped each other due to same longitudinal position and by changing the position 's' of front bogie.

The force elements for the secondary suspension is created between the markers of car-body and bogie frame [9].

CAR BODY GEOMETRY PROPI	INDIAN TYPE LHB COACH	ITALIAN TYPE CARBODY
Mass of car-body	33740 kg	32000 kg
Inertia I_{XX}	56932 kg m²	56000 kg m²
Inertia I_{YY}	1307220 kg m²	2.e⁶ kg m²
Inertia I_{ZZ}	1309744 kg m²	2.e⁶ kg m²
Position of z from cg point	1.8 m	1.8 m
Length in X L1	23.54 m	22 m
Width W1	3.2	2.79 m
Height H1	4.09 m	-
Longitudinal joint position	8.63 m	10.75 m
Bogie – bogie distance	16.2 m	19 m
Position of WS1 from track	17.3 m	
Position of WS 2 from track	14.74 m	

Table.11 Car body properties

SUSPENSION PARAMETERS	INDIAN TYPE COACH	ITALIAN TYPE MODEL
Stiffness k_X	175000 N/m	150000 N/m
Stiffness K_Y	175000 N/m	150000 N/m
Stiffness K_Z	450000 N/m	450000 N/m
Damping d_X	35000 Ns/m	32000 Ns/m
Damping d_Y	35000 Ns/m	32000 Ns/m
Damping d_Z	23000 Ns/m	20000 Ns/m

Table.12 Secondary Suspension properties

The entire vehicle model contains two bogies and two stages of suspension systems. Each bogie consists of two solid wheelsets.

Car-Body Modelling Process :-

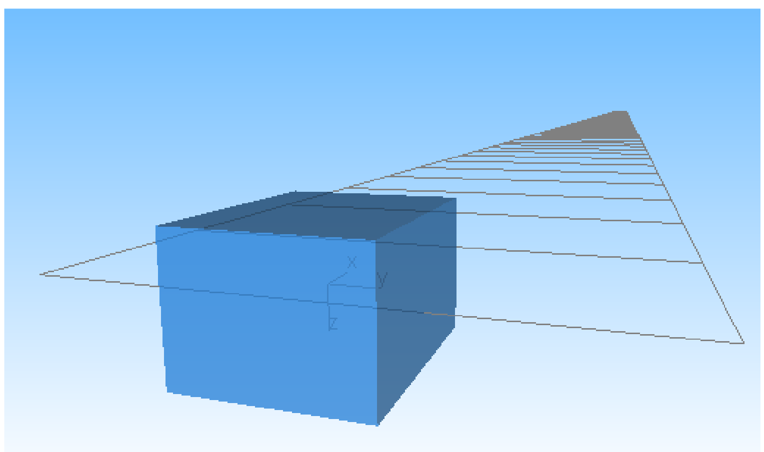


Fig.3.11 Rail track model

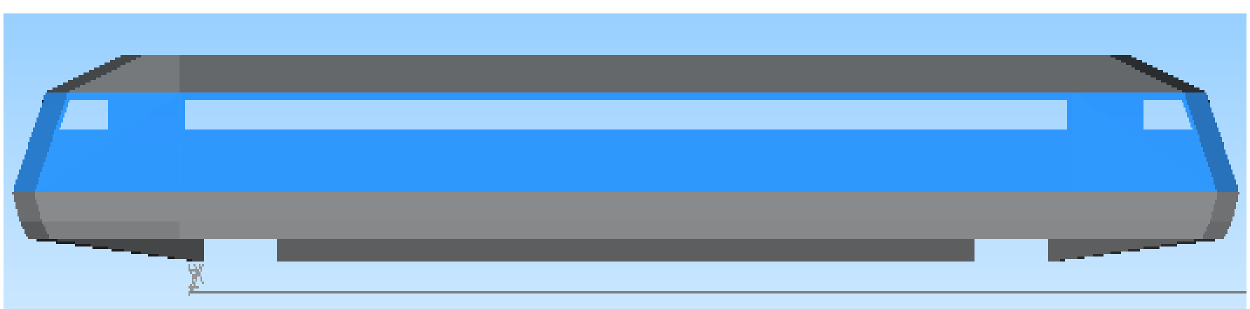


Fig.3.12 Car-body model

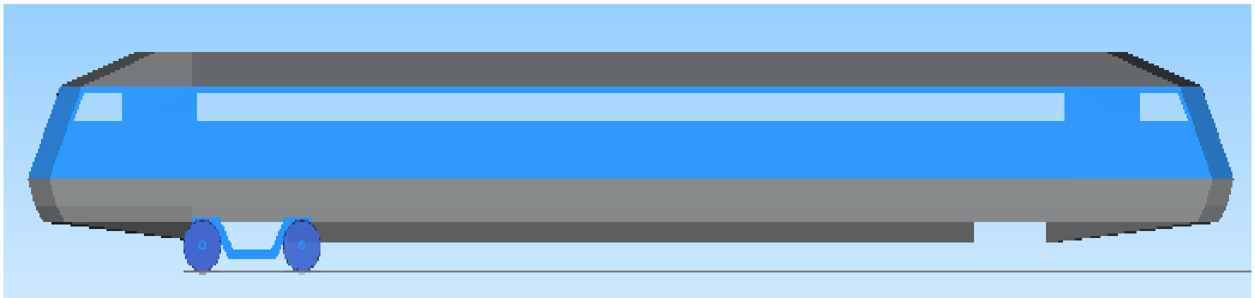


Fig.3.13 Car-body with bogie and wheelset

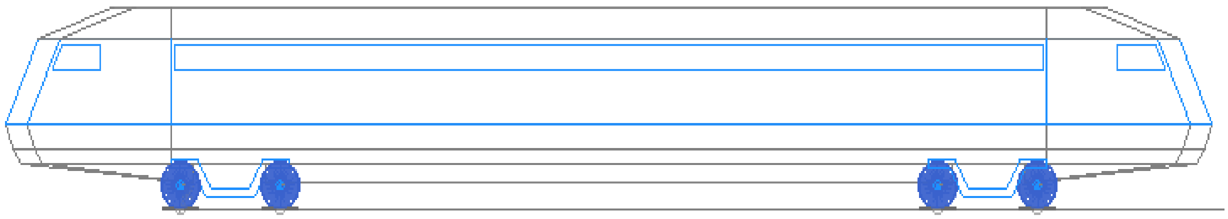


Fig.3.14 Car-body with complete model in wireframe representation

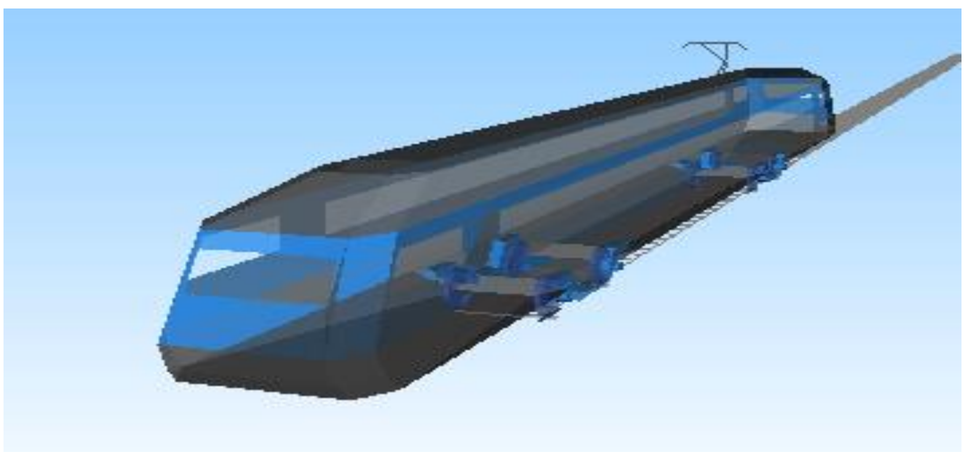


Fig.3.15 Entire vehicle model

Modal Check :-

The model is checked with preload conditions to get lower residual acceleration value and the value of force components in vertical direction i.e. z direction behaves in a symmetrical approach. The secondary suspension force after the preload process should be equal to mass of car-body*9.81/4. Here 4 indicates the number of components placed [6].

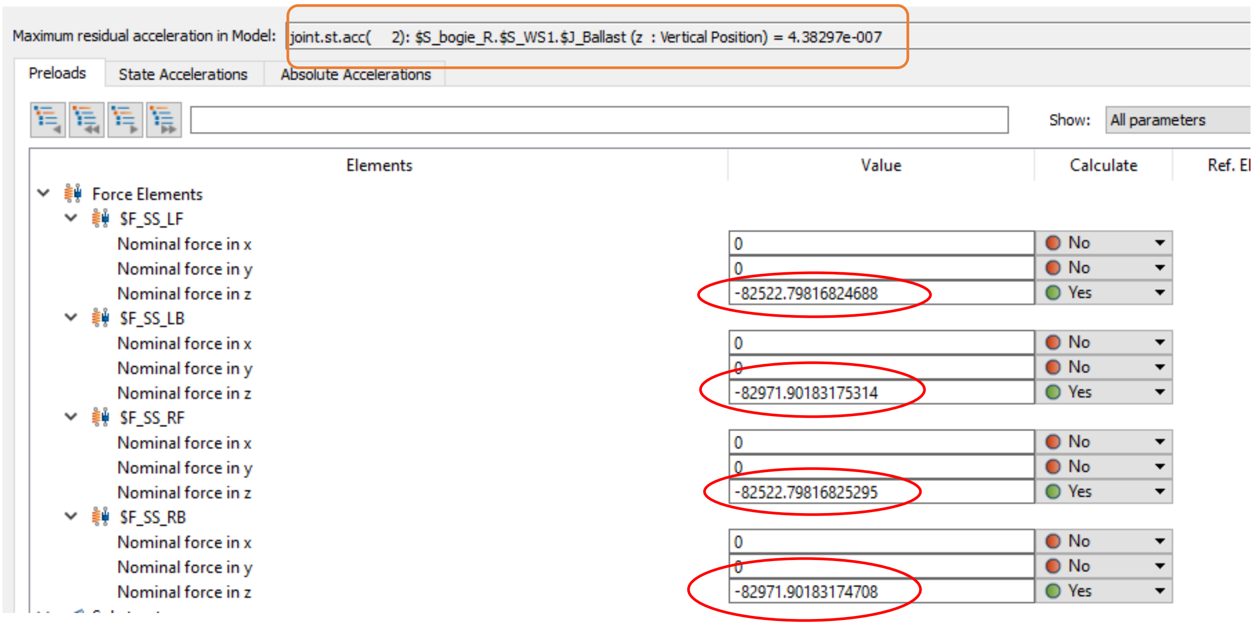


Fig.3.16 Preload model check

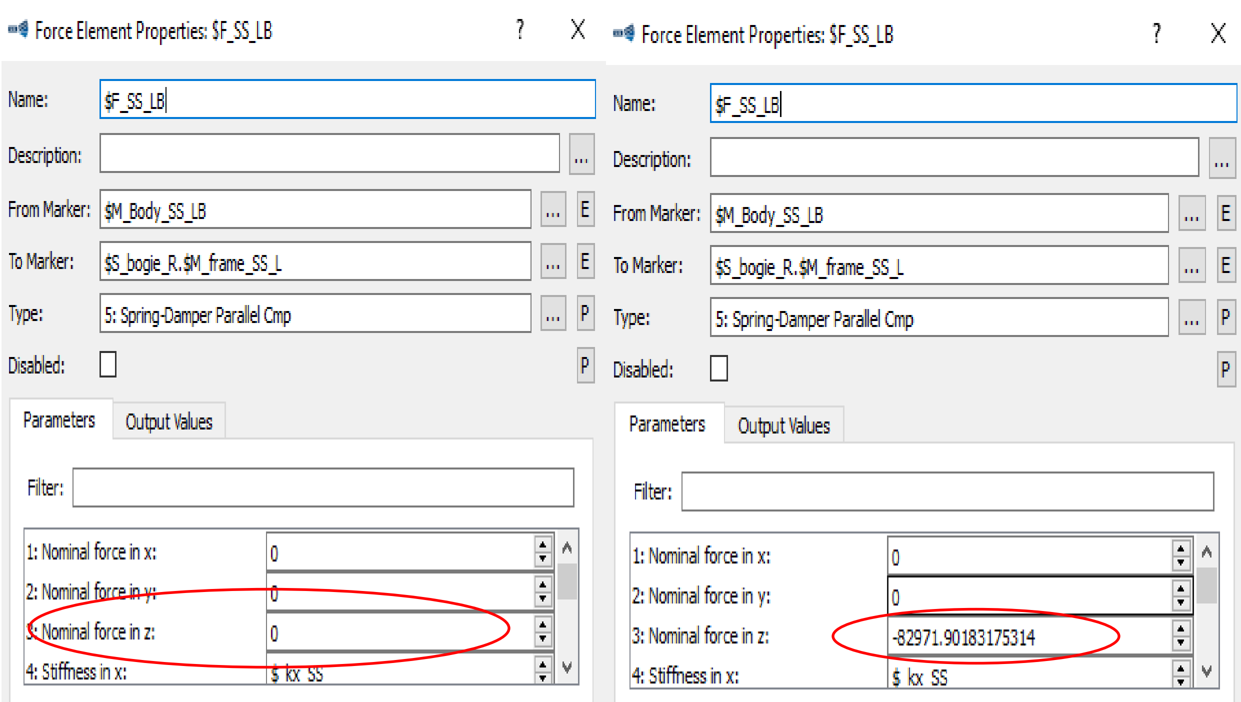


Fig.3.17 Force elements (Secondary Suspension) Left Back Bogie before and after preload check

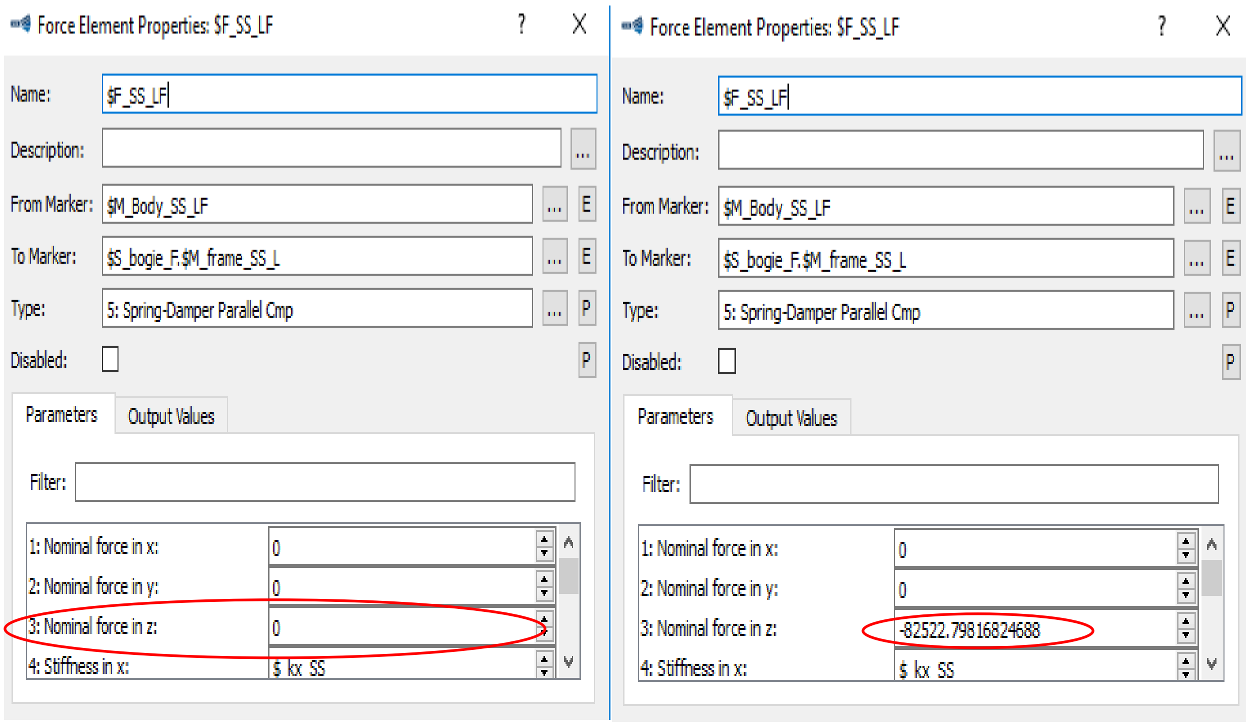


Fig.3.18 Force elements (Secondary Suspension) Left Front Bogie before and after preload check

3.2 Track Model :-

Cartographic track model kind of track is used, and this assembled from various segments in all three directions horizontal, super-elevation and vertical that are stringed together [8].

ABBREVIATION	DESCRIPTION
STR	Straight (tangent) track
CIR	Circular arc
CLO	Clothoid transition, the curvature increases or decreases linearly by 1/R1 to 1/R2.

Table.13 Cartographic Horizontal track model with description

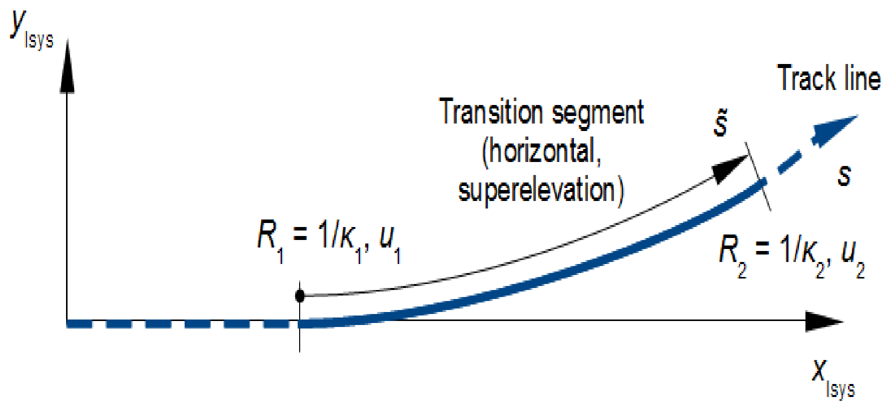
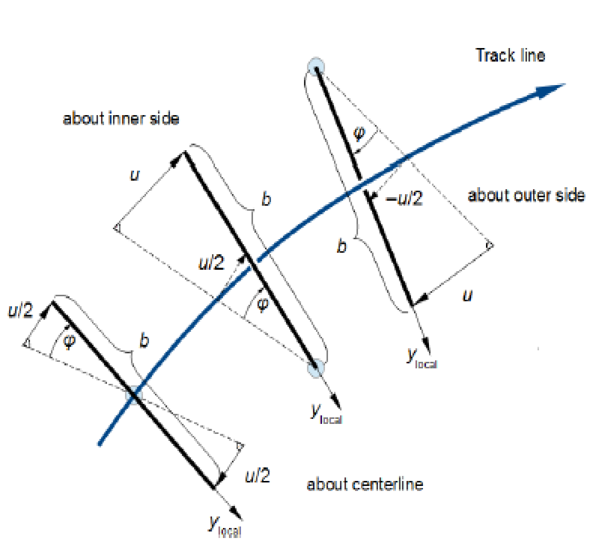
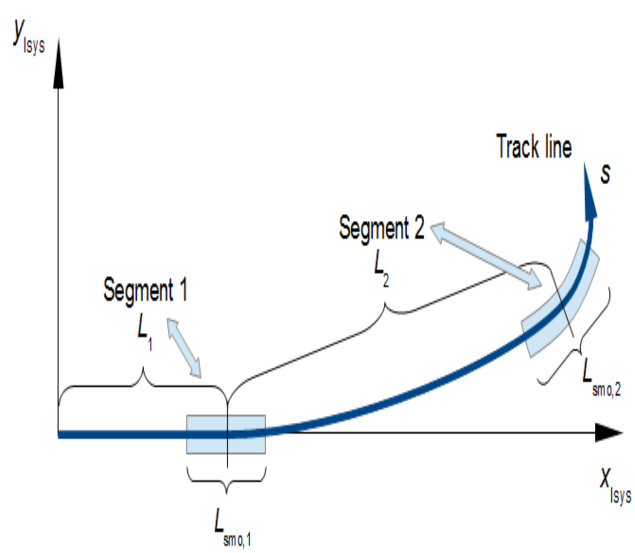


Fig.3.19 Horizontal track model with transition segment

Abbreviation	Description
CST	Constant super-elevation
LIR	Linear ramp, the super-elevation increases or decreases linearly from u_1 to u_2

Table.14 Cartographic Super-elevation track model with description





A positive super-elevation corresponds to a right-hand curve and negative super-elevation corresponds to a left-hand curve.

3.2.1 Track Irregularity :-

Track excitation in addition has superimposed irregularities to the track layout. Track related to additional irregularities for all movements in track and rail are listed below.

TRACK RELATED EXCITATION :-

- Lateral excitation
- Vertical excitation
- Roll angular excitation
- Gauge excitation

RAIL RELATED EXCITATION :-

- Left lateral excitation
- Right lateral excitation
- Left vertical excitation
- Right vertical excitation

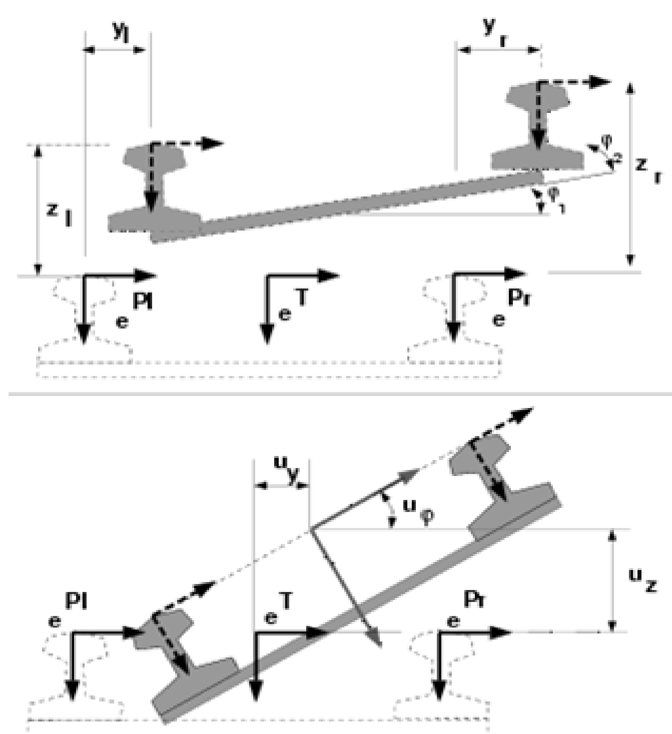


Fig.3.20 Excitation type

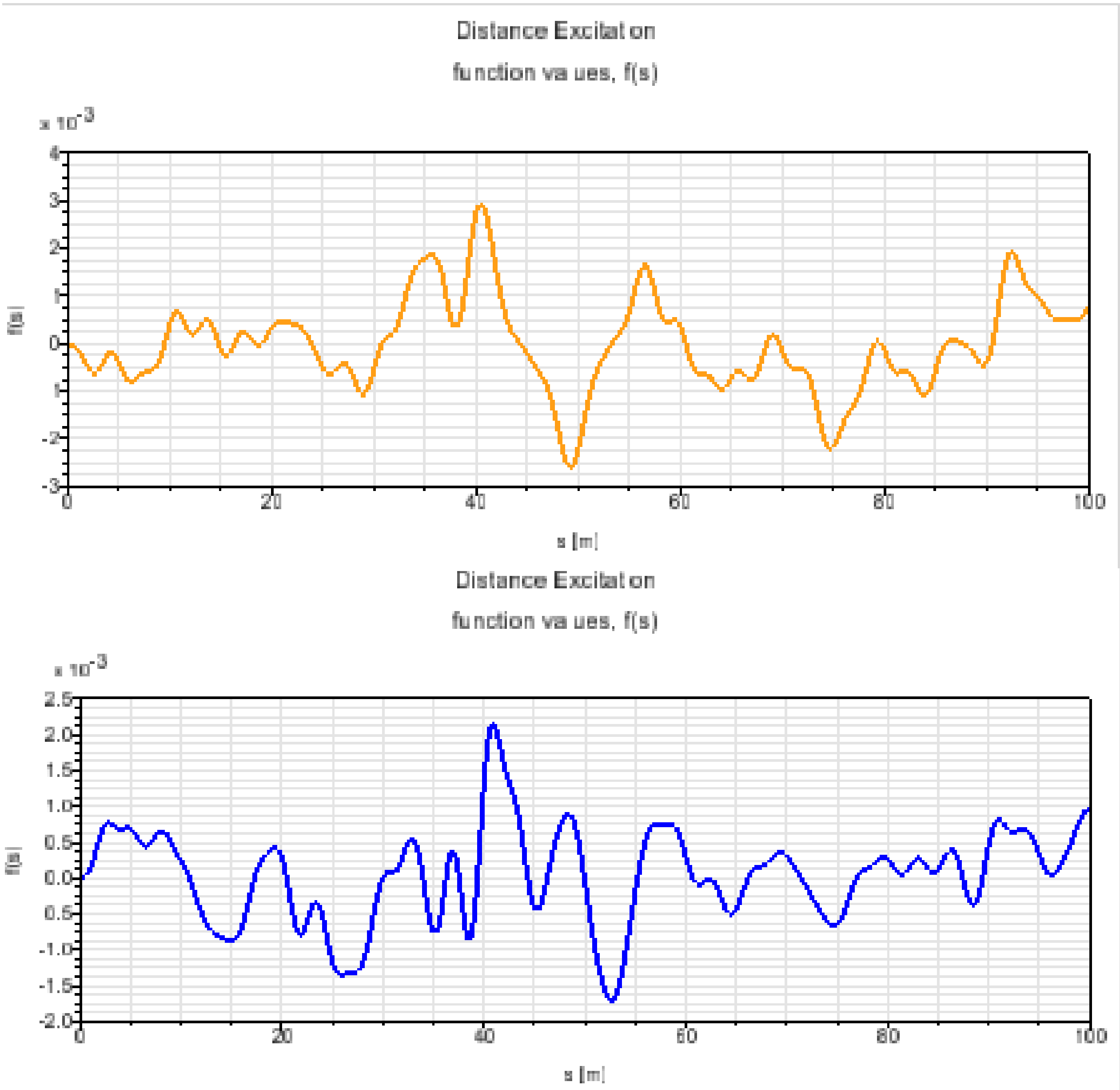
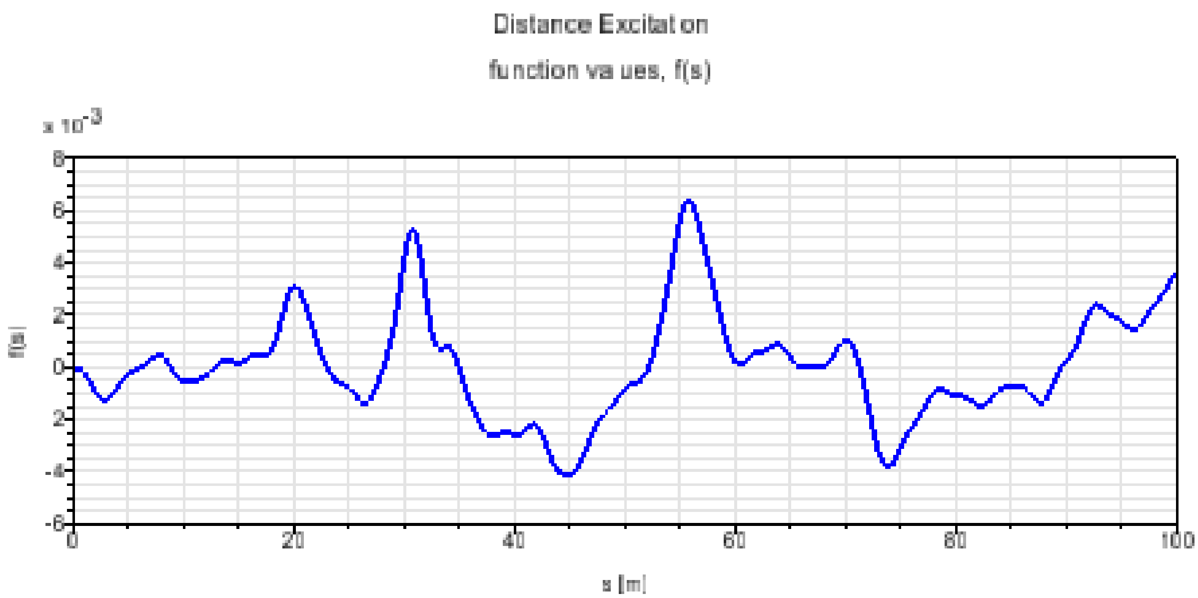


Fig.3.21 Excitation lateral left and right



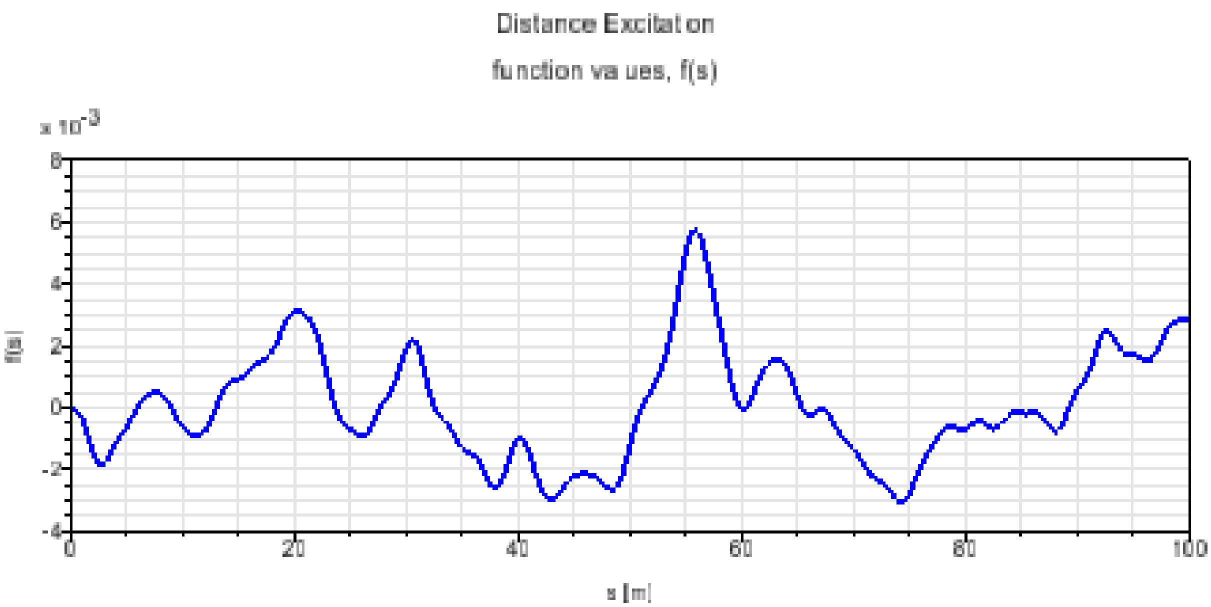


Fig.3.22 Excitation vertical left and right

3.2.2 Track Layout for Test Zones :-

Test Zone 1 - Track Model :-

The line designed for this type of zone according to EN14363 standard should be of straight (tangent) line for a minimal of 10 kms in length.

The excitation in the track model is at the starting position of track and given fade in/out length distance to be 50 till the end of the track. All excitations type of rail related (both lateral and vertical) on left and right are considered.

Test Zone 2 Track Model :-

The track designed for this type of tests should have straight and very large radius curve. The length of the track is targeted for about 10 kms, in which there are 5 curve sections both right- and left-hand curve. The curve radius designed for this type of test zone are met with test conditions (velocity of train and cant deficiency)

TYPE OF TRACK	DESCRIPTION	PART 1	DESCRIPTION	PART 2	DESCRIPTION	PART 3
Straight	Length	500	-	-	-	-
Transition	Length	100	RADIUS R1	0	RADIUS R2	1520
Circular	Length	1250	RADIUS R	1520		
Transition	Length	100	RADIUS R1	1520	RADIUS R2	0
Straight	Length	500	-	-	-	-
Transition	Length	100	RADIUS R1	0	RADIUS R2	-1600
Circular	Length	1250	RADIUS R	-1600		
Transition	Length	100	RADIUS R1	-1600	RADIUS R2	0
Straight	Length	500	-	-	-	-
Transition	Length	100	RADIUS R1	0	RADIUS R2	1800

n						
Circular	Length	1250	RADIUS R	1800		
Transition	Length	100	RADIUS R1	1800	RADIUS R2	0
Straight	Length	300	-	-	-	-
Transition	Length	100	RADIUS R1	0	RADIUS R2	-1900
Circular	Length	1250	RADIUS R	-1900		
Transition	Length	100	RADIUS R1	-1900	RADIUS R2	0
Straight	Length	500	-	-	-	-
Transition	Length	150	RADIUS R1	0	RADIUS R2	1950
Circular	Length	1250	RADIUS R	1950		
Transition	Length	150	RADIUS R1	1950	RADIUS R2	0
Straight	Length	500	-	-	-	-

Table.15 Horizontal track layout parameters

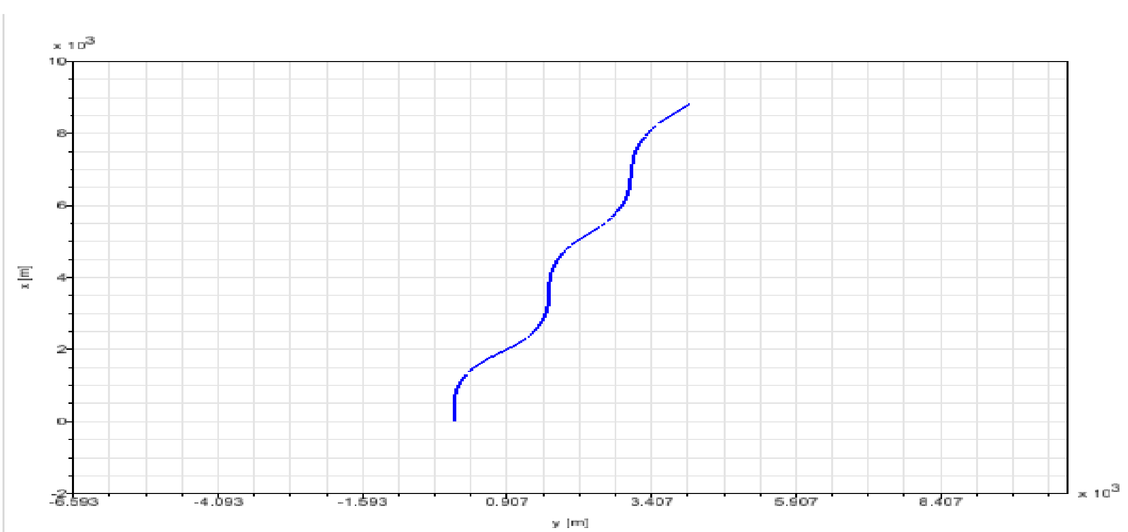


Fig.3.23 Test zone 2 track layout

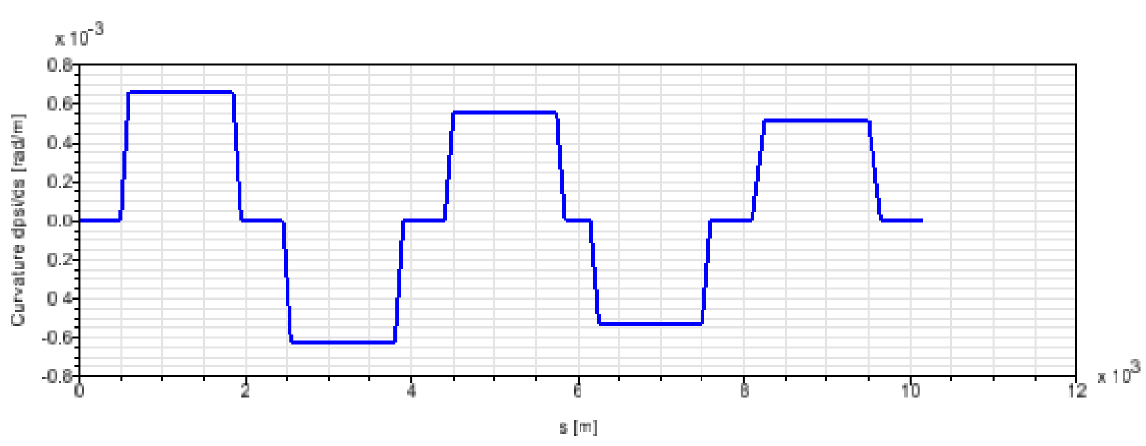


Fig.3.24 Curve layout model test zone 2

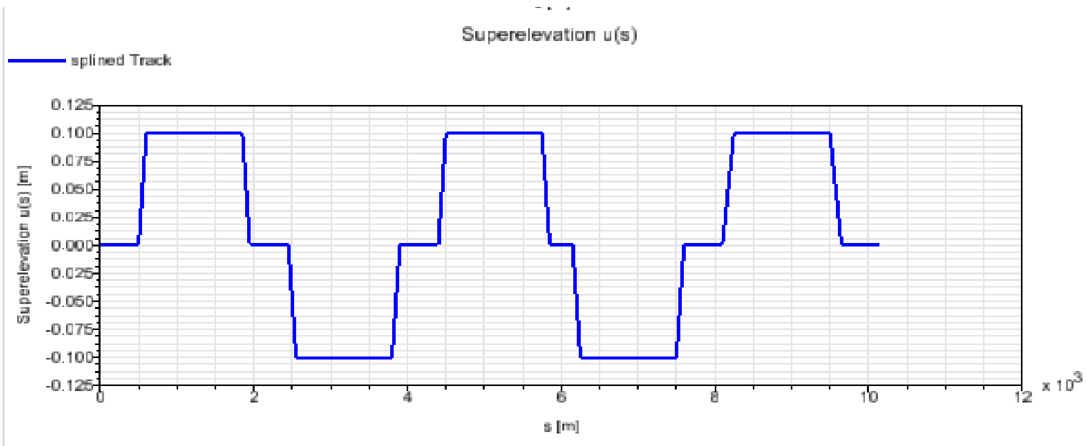


Fig.3.25 Super-elevation layout model test zone 2

TYPE OF TRACK	DES-CRIPTION	PART 1	DES-CRIPTION	PART 2	DES-CRIPTION	PART 3
Constant	Length	500	Super elevation U	0	-	-
Linear	Length	100	Super elevation U1	0	RADIUS R2	0.1
Constant	Length	1250	Super elevation U	0.1		
Linear	Length	100	Super elevation U1	0.1	RADIUS R2	0
Constant	Length	500	Super elevation U	-	-	-
Linear	Length	100	Super elevation U1	0	RADIUS R2	-0.1
Constant	Length	1250	Super elevation U	-0.1		

Linear	Length	100	Super elevation U1	-0.1	RADIUS R2	0
Constant	Length	500	Super elevation U	-	-	-
Linear	Length	100	Super elevation U1	0	RADIUS R2	0.1
Constant	Length	1250	Super elevation U	0.1		
Linear	Length	100	Super elevation U1	0.1	RADIUS R2	0
Constant	Length	300	Super elevation U	-	-	-
Linear	Length	100	Super elevation U1	0	RADIUS R2	-0.1
Constant	Length	1250	Super elevation U	-0.1		
Linear	Length	100	Super elevation U1	-0.1	RADIUS R2	0
Constant	Length	500	Super elevation U	-	-	-
Linear	Length	150	Super elevation U1	0	RADIUS R2	0.1
Constant	Length	1250	Super elevation U	0.1		
Linear	Length	150	Super elevation U1	0.1	RADIUS R2	0
Constant	Length	500	Super elevation U	-	-	-

Table. 16 Super-elevation track layout parameters

The excitation in the track model is at the starting position of track and given fade in/out length distance to be 50 till the end of the track. All excitations type of rail related (both lateral and vertical) on left and right are considered.

Test Zone 3 Track Model :-

This type of test zone model is targeted for small radius curves (400 m ≥ R ≤ 600 m) . The length of the track is almost nearer to 8 kms, in which there are 5 curve sections both right- and left-hand curve. The curve radius designed for this type of test zone are met with test conditions (velocity of train and cant deficiency)

TYPE OF TRACK	DESCRIPTION	PART 1	DESCRIPTION	PART 2	DESCRIPTION	PART 3
Straight	Length	350	-	-	-	-
Transition	Length	100	RADIUS R1	0	RADIUS R2	450
Circular	Length	1000	RADIUS R	450		
Transition	Length	100	RADIUS R1	450	RADIUS R2	0
Straight	Length	300	-	-	-	-
Transition	Length	100	RADIUS R1	0	RADIUS R2	-500
Circular	Length	1000	RADIUS R	-500		
Transition	Length	100	RADIUS R1	-500	RADIUS R2	0
Straight	Length	300	-	-	-	-
Transition	Length	100	RADIUS R1	0	RADIUS R2	530
Circular	Length	1000	RADIUS R	530		
Transition	Length	100	RADIUS R1	530	RADIUS R2	0
Straight	Length	300	-	-	-	-
Transition	Length	100	RADIUS R1	0	RADIUS R2	-550
Circular	Length	1000	RADIUS R	-550		
Transition	Length	100	RADIUS R1	-550	RADIUS R2	0
Straight	Length	300	-	-	-	-
Transition	Length	100	RADIUS R1	0	RADIUS R2	580
Circular	Length	1000	RADIUS R	580		
Transition	Length	100	RADIUS R1	580	RADIUS R2	0
Straight	Length	350	-	-	-	-

Table.17 Horizontal track layout parameters

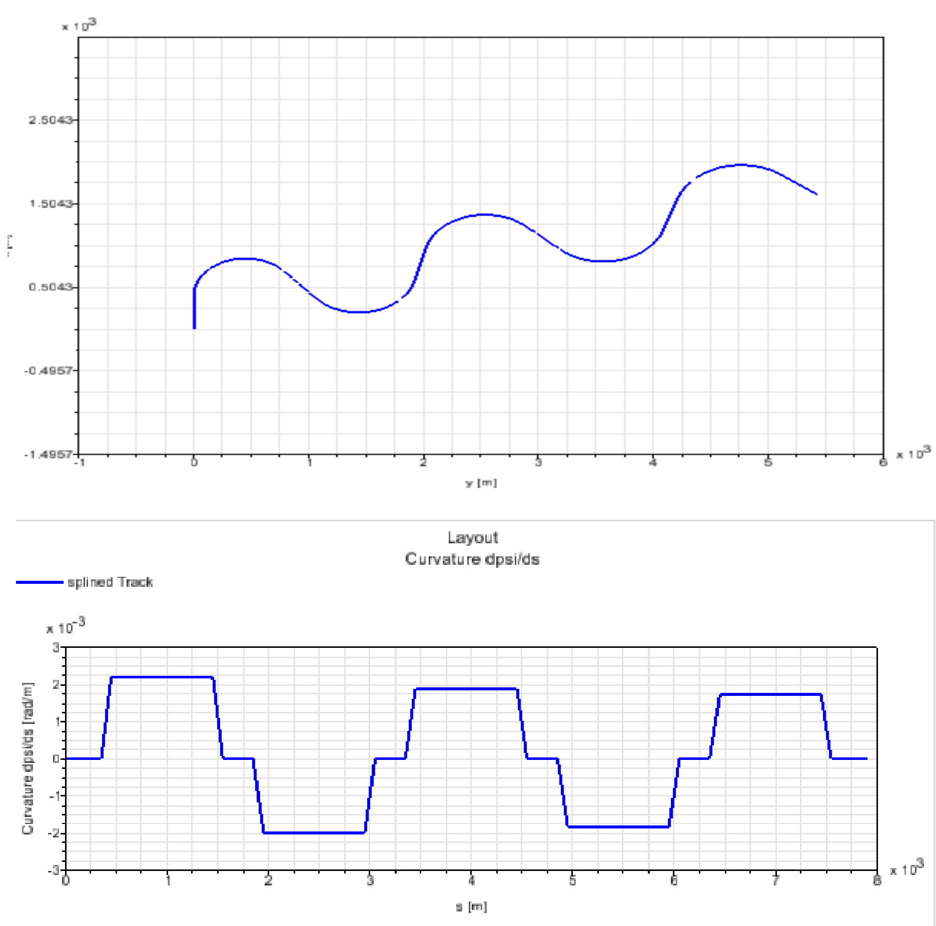


Fig.3.26 Test zone 3 curve layout model

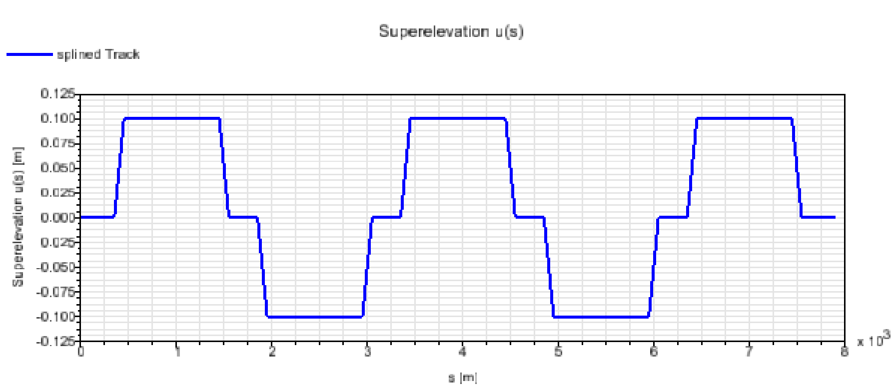


Fig.3.27 Test zone 3 super-elevation model

TYPE OF TRACK	DESCRIPTION	PART 1	DESCRIPTION	PART 2	DESCRIPTION	PART 3
Constant	Length	350	Super elevation U	0	-	-
Linear	Length	100	Super	0	RADIUS R2	0.1

			elevation U1			
Constant	Length	1000	Super elevation U	0.1		
Linear	Length	100	Super elevation U1	0.1	RADIUS R2	0
Constant	Length	300	Super elevation U	-	-	-
Linear	Length	100	Super elevation U1	0	RADIUS R2	-0.1
Constant	Length	1000	Super elevation U	-0.1		
Linear	Length	100	Super elevation U1	-0.1	RADIUS R2	0
Constant	Length	300	Super elevation U	-	-	-
Linear	Length	100	Super elevation U1	0	RADIUS R2	0.1
Constant	Length	1000	Super elevation U	0.1		
Linear	Length	100	Super elevation U1	0.1	RADIUS R2	0
Constant	Length	300	Super elevation U	-	-	-
Linear	Length	100	Super elevation U1	0	RADIUS R2	-0.1
Constant	Length	1000	Super elevation U	-0.1		
Linear	Length	100	Super elevation U1	-0.1	RADIUS R2	0
Constant	Length	300	Super elevation U	-	-	-
Linear	Length	100	Super elevation U1	0	RADIUS R2	0.1
Constant	Length	1000	Super elevation U	0.1		
Linear	Length	100	Super elevation U1	0.1	RADIUS R2	0
Constant	Length	350	Super elevation U	-	-	-

Table. 18 Super-elevation track layout parameters

The excitation in the track model is at the starting position of track and given fade in/out length distance to be 50 till the end of the track. All excitations type of rail related (both lateral and vertical) on left and right are considered.

Test Zone 4 Track Model :-

This type of test zone model is targeted for very small radius curves (250 m ≥ R < 400 m) . The length of the track is kms, in which there are 5 curve sections both right- and left-hand curve. The curve radius designed for this type of test zone are met with test conditions (velocity of train and cant deficiency)

TYPE OF TRACK	DESCRIPTION	PART 1	DESCRIPTION	PART 2	DESCRIPTION	PART 3
Straight	Length	400	-	-	-	-
Transition	Length	100	RADIUS R1	0	RADIUS R2	320
Circular	Length	350	RADIUS R	320		
Transition	Length	100	RADIUS R1	320	RADIUS R2	0
Straight	Length	400	-	-	-	-
Transition	Length	100	RADIUS R1	0	RADIUS R2	-360
Circular	Length	350	RADIUS R	-360		
Transition	Length	100	RADIUS R1	-360	RADIUS R2	0
Straight	Length	450	-	-	-	-
Transition	Length	100	RADIUS R1	0	RADIUS R2	340
Circular	Length	350	RADIUS R	340		
Transition	Length	100	RADIUS R1	340	RADIUS R2	0
Straight	Length	450	-	-	-	-
Transition	Length	100	RADIUS R1	0	RADIUS R2	-285
Circular	Length	350	RADIUS R	-285		
Transition	Length	100	RADIUS R1	-285	RADIUS R2	0
Straight	Length	450	-	-	-	-
Transition	Length	100	RADIUS R1	0	RADIUS R2	370
Circular	Length	350	RADIUS R	370		
Transition	Length	100	RADIUS R1	370	RADIUS R2	0
Straight	Length	300	-	-	-	-

Table.19 Horizontal track layout parameters

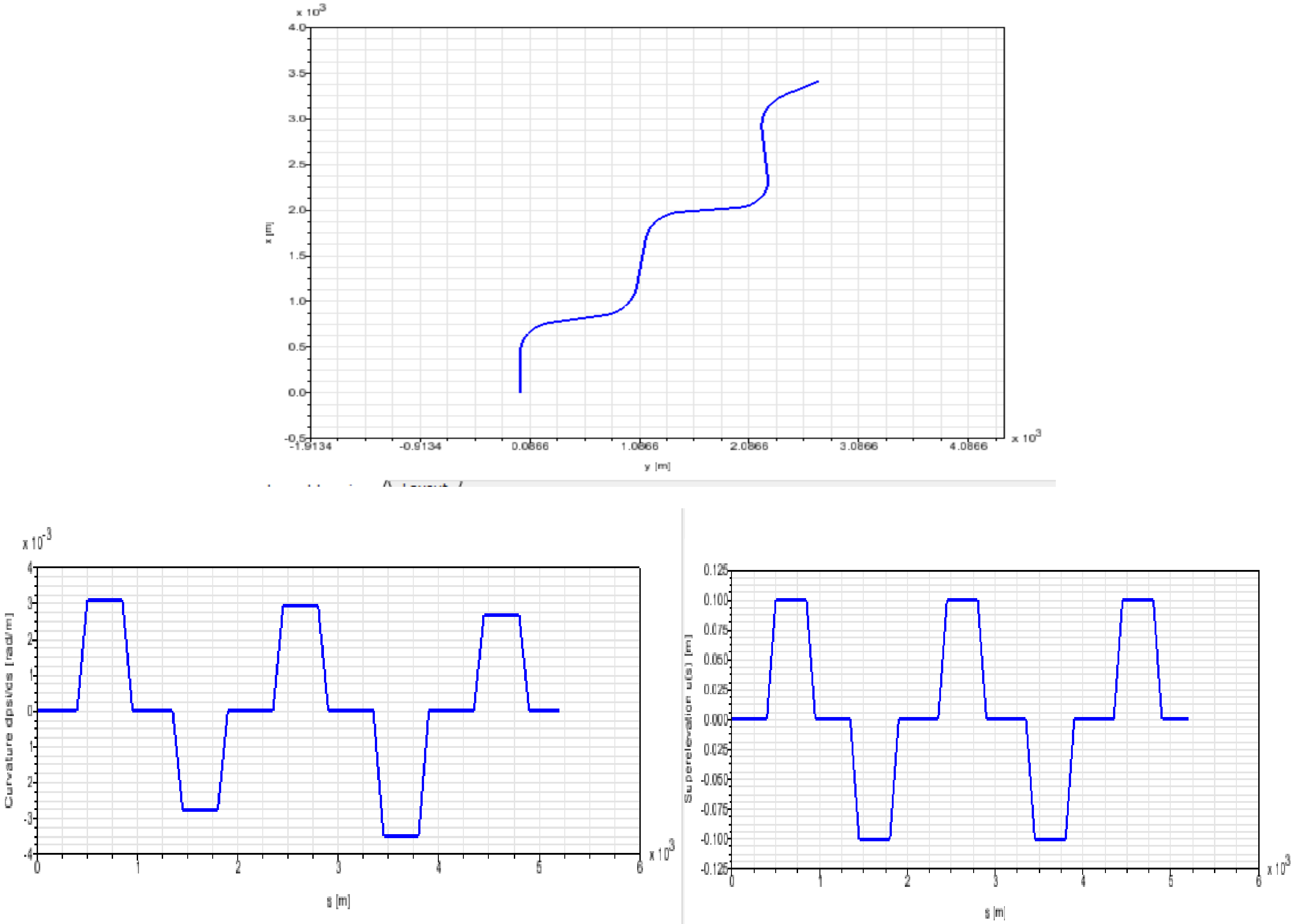


Fig.3.28 Curve and super-elevation layout model test zone 4

TYPE OF TRACK	DESCRIPTION	PART 1	DESCRIPTION	PART 2	DESCRIPTION	PART 3
Constant	Length	400	Super elevation U	0	-	-
Linear	Length	100	Super elevation U1	0	RADIUS R2	0.1
Constant	Length	350	Super elevation U	0.1		
Linear	Length	100	Super elevation U1	0.1	RADIUS R2	0
Constant	Length	400	Super elevation U	-	-	-
Linear	Length	100	Super elevation	0	RADIUS R2	-0.1

			U1			
Constan t	Length	350	Super elevation U	-0.1		
Linear	Length	100	Super elevation U1	-0.1	RADIUS R2	0
Constan t	Length	450	Super elevation U	-	-	-
Linear	Length	100	Super elevation U1	0	RADIUS R2	0.1
Constan t	Length	350	Super elevation U	0.1		
Linear	Length	100	Super elevation U1	0.1	RADIUS R2	0
Constan t	Length	450	Super elevation U	-	-	-
Linear	Length	100	Super elevation U1	0	RADIUS R2	-0.1
Constan t	Length	350	Super elevation U	-0.1		
Linear	Length	100	Super elevation U1	-0.1	RADIUS R2	0
Constan t	Length	450	Super elevation U	-	-	-
Linear	Length	100	Super elevation U1	0	RADIUS R2	0.1
Constan t	Length	350	Super elevation U	0.1		
Linear	Length	100	Super elevation U1	0.1	RADIUS R2	0
Constan t	Length	300	Super elevation U	-	-	-

Table.20 Super-elevation track layout parameters

The excitation in the track model is at the starting position of track and given fade in/out length distance to be 50 till the end of the track. All excitations type of rail related (both lateral and vertical) on left and right are considered.

Chapter 4

4. Simulations According to EN:14363 :-

In this chapter results from simulations with track design geometry and vehicle speeds following the standard EN 14363 are presented with figures and values for the assessment quantities. All accelerations are band-pass filtered between 0.4 – 10 Hz and all the forces are low pass filtered for 10 Hz which is the procedure for running safety and ride characteristics [3].

The vehicle's limit values for sum of lateral forces, $\sum Y_{MAX}$

$\sum Y_{MAX\ ,\ LIMIT}$ [KN]	65.59
$\sum Y_{RMS\ ,\ LIMIT}$	32.71

The vehicle's limit values for Quotient of guiding force and wheel force, (Y/Q)

$(Y/Q)_{MAX,LIMIT}$	0.8

The vehicle's limit values for Quasi-static guiding force, Y_{QST} (FOR TEST ZONE 2,3,4)

$Y_{QST,LIMIT}$ [KN]	60

The vehicle's limit value for Quasi-static wheel force, Q_{QST} (FOR TEST ZONE 2,3,4)

$Q_{QST,LIMIT}$ [KN]	145

The vehicle's limit value for Maximum wheel force, Q_{MAX}

$Q_{MAX,LIMIT}$ [KN]	90+166.77/2 = 173.385

4.1 Test Zone 1, Tangent Track :-

For this zone with this desired maximum speed of the vehicle at 160 kmph (operating speed) the test speed becomes 181 kmph according to Table. 4

4.1.1 Stability Assessment Using Simulations :-

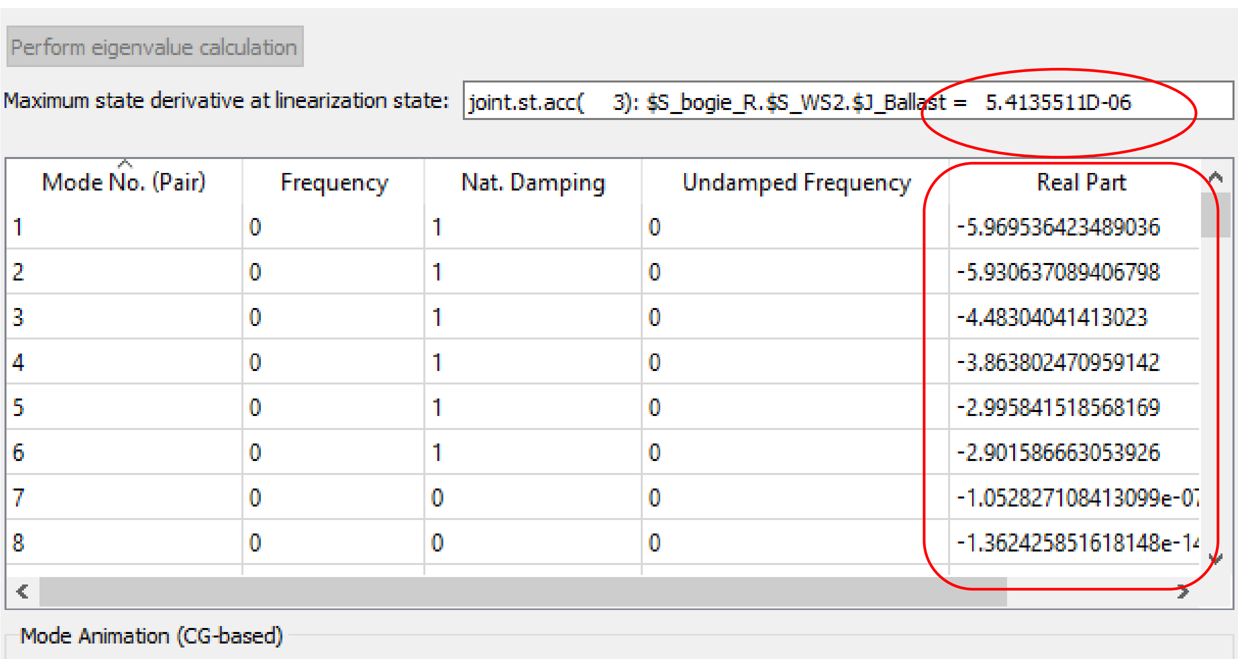
Linear stability :- Assessing stability based on linearized system.

General form of equation of motion of vehicle :

$$M\ddot{u} + \left[D_{\mathrm{D}} + \frac{1}{v_0} D_{\mathrm{C}} \right] \dot{u} + [\, S_{\mathrm{P}} + S_{\mathrm{F}} + S_{\mathrm{C}} \,]\, u = 0.$$

The factor $(1/v_0)$ in-front of D_c implies that the amount of damping that this matrix contributes decrease with increase of vehicle speed.

The linearized model eigen value system (the vehicle speed where the real part is zero is called linear critical speed V_{cric}) is used to obtain the dynamic behavior of vehicle.



Mode No. (Pair)	Frequency	Nat. Damping	Undamped Frequency	Real Part
1	0	1	0	-5.969536423489036
2	0	1	0	-5.930637089406798
3	0	1	0	-4.48304041413023
4	0	1	0	-3.863802470959142
5	0	1	0	-2.995841518568169
6	0	1	0	-2.901586663053926
7	0	0	0	-1.052827108413099e-07
8	0	0	0	-1.362425851618148e-14

Fig.4.1 Eigen value calculation for test zone 1

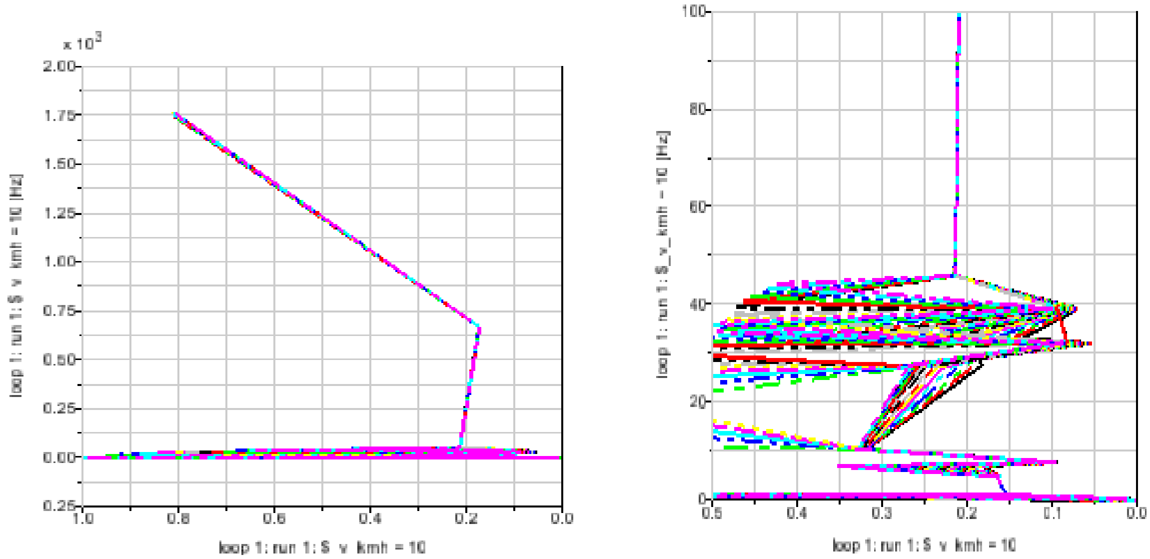
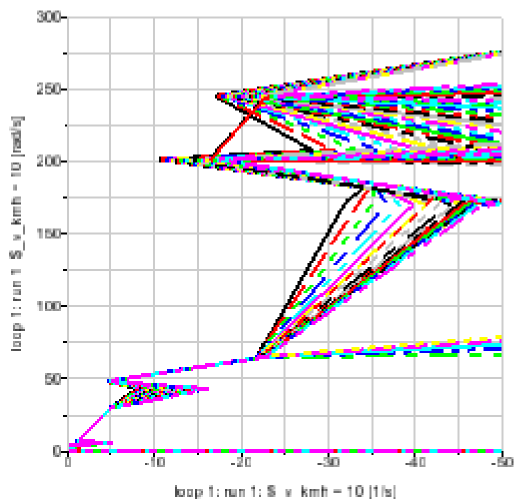


Fig.4.2 Function of Damping vs frequency



Imaginary vs Real part (Root loci curve)

The stability results on the figure above show us the system remains stable for both operating (160 kmph)and test speeds (181 kmph) as it falls in the negative real part for all loop runs.

4.2 Test Zone 2 (Large Radius Curve) :-

The test speed (169 kmph) and radius of curvature R for this zone must be satisfied in the following test conditions. Here speed and cant deficiency act as an influencing factor for running conditions.

Non – compensated acceleration (admissible) = 0.8 m/s^2

Wheel-set gauge = 1727 mm

Cant deficiency admissible cd_{ADM}= 0.8 * 1727 / 9.81 = 141 mm

Cant deficiency minimum cd_{MIN} = 141 * 0.7 = 99 mm

Cant deficiency maximum cd_{MAX} = 141 * 1.15 = 162 mm

Cant deficiency N2 section = 141 * 1.05 = 148 mm

Minimum velocity of vehicle @ TZ 2 = 155 kmph

Maximum velocity of vehicle @ TZ 2 = 181 kmph

Super elevation h = 100 mm

Non fully compensated centrifugal force by weight component

$$\frac{h}{s} = \frac{m(\frac{v2}{R} - anc)}{mg}$$

The Radius of curvature can be found out using this formula.

4.2.1 Stability Assessment Test Zone 2 :-

The stability results on the figure below show us the system remains stable for both operating (160 kmph)and test speeds (169 kmph) as it falls in the negative real part for all loop runs.

Maximum state derivative at linearization state: joint.st.acc(3): $S_bogie_F.$S_WS2.$J_Ballast = 1.0339692D-05

Mode No. (Pair)	Frequency	Nat. Damping	Undamped Frequency	Real Part
1	0	1	0	-5.969523934398212
2	0	1	0	-5.930637204965734
3	0	1	0	-4.483037460408261
4	0	1	0	-3.863796808471796
5	0	1	0	-2.995847759025863
6	0	1	0	-2.90159017216002
7	0	0	0	-2.13033953696569e-06
8	0	0	0	-2.119885241956772e-07

Fig.4.3 Eigen value calculation test zone 2

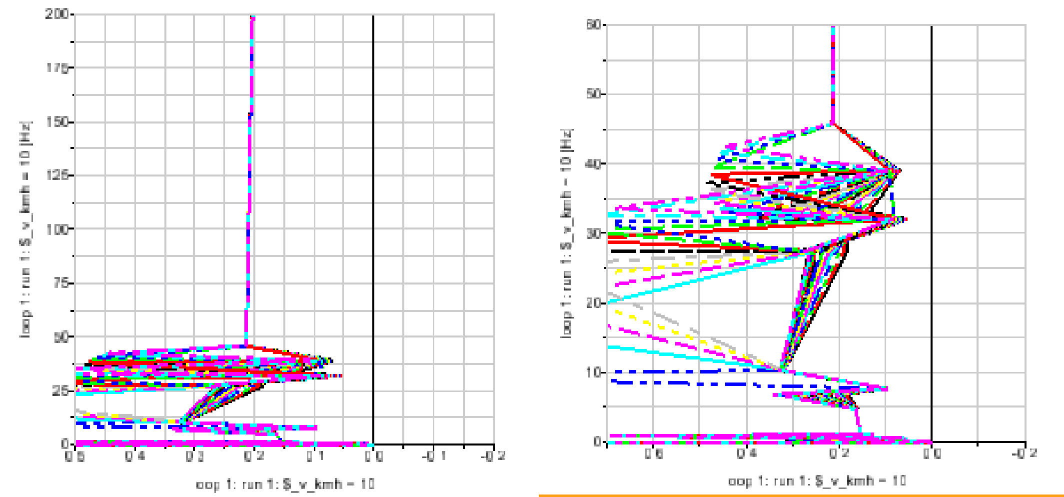
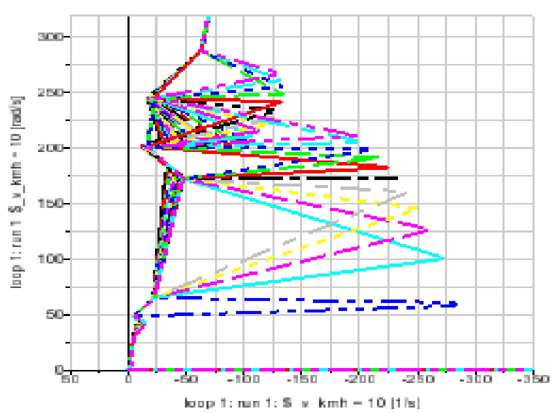


Fig.4.4 Function of damping vs frequency



Imaginary vs Real part (Root locus curve)

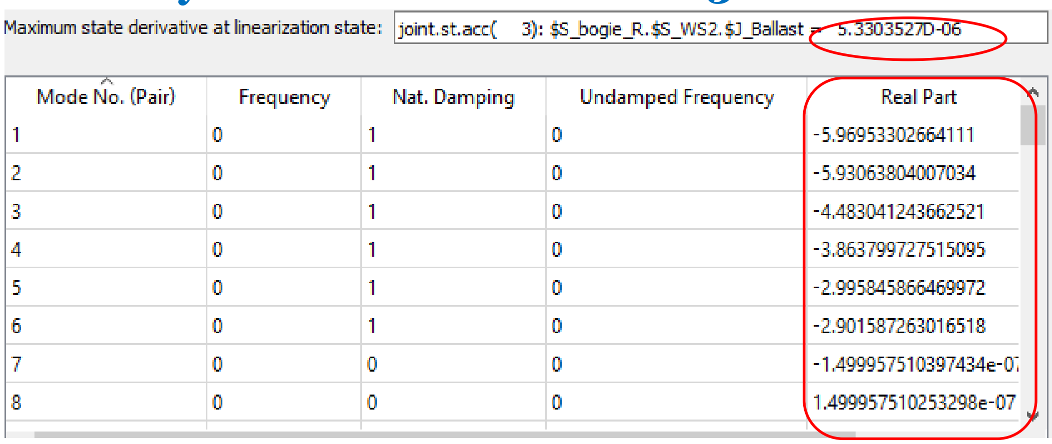
4.3 Test Zone 3 (Small Radius Curve) :-

Here, the radius of test zone R_{MIN} (400 m)and R_{MAX} (600 m)are known. The minimum and maximum speed of the vehicle can be calculated using the formula mentioned in test zone 2.

The test speed for the radius of curvature must satisfy the non-compensated acceleration a_{nc} and it should be below 0.8 m/s².

Here cant deficiency act as an influencing factor than the speed of vehicle.

4.3.1 Stability Assessment Test Zone 3:-



Maximum state derivative at linearization state: joint.st.acc(3): $S_bogie_R.$S_WS2.$J_Ballast = 5.3303527D-06

Mode No. (Pair)	Frequency	Nat. Damping	Undamped Frequency	Real Part
1	0	1	0	-5.96953302664111
2	0	1	0	-5.93063804007034
3	0	1	0	-4.483041243662521
4	0	1	0	-3.863799727515095
5	0	1	0	-2.995845866469972
6	0	1	0	-2.901587263016518
7	0	0	0	-1.499957510397434e-07
8	0	0	0	1.499957510253298e-07

Fig.4.5 Eigen value calculation test zone 3

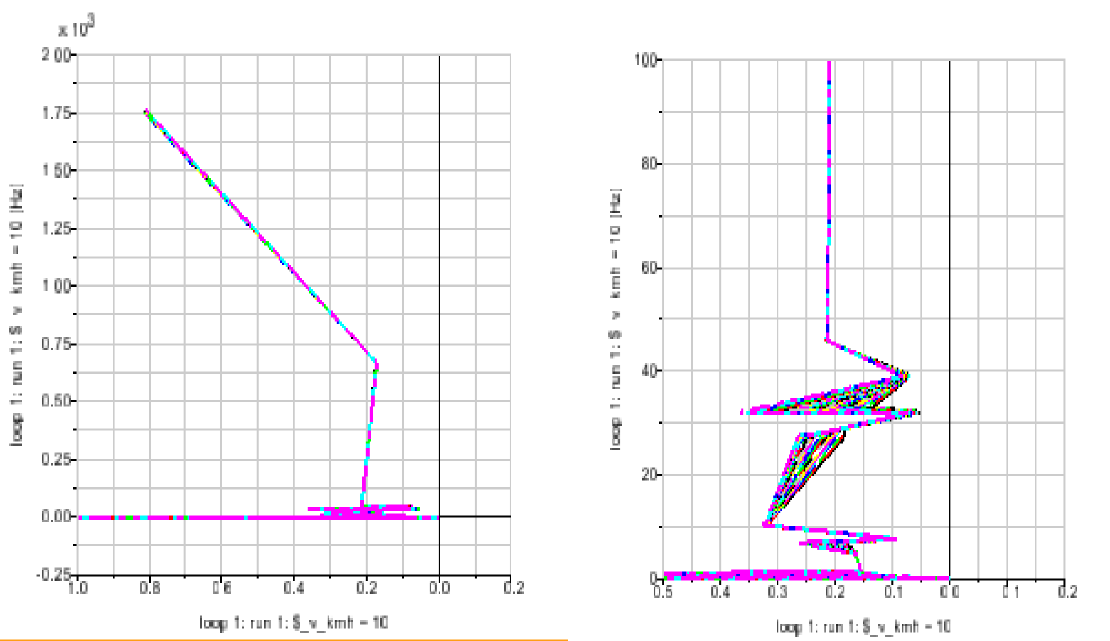
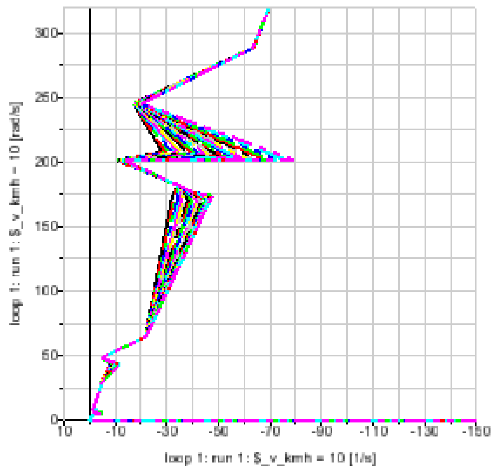


Fig.4.6 Function of damping vs frequency



Imaginary vs Real (Root locus curve)

4.4 Test Zone 4 (Very Small Radius Curve) :-

Here, the radius of test zone R_{MIN} (250 m)and R_{MAX} (399 m)are known. The minimum and maximum speed of the vehicle can be calculated using the formula mentioned in test zone 2.

The test speed for the radius of curvature must satisfy the non-compensated acceleration a_{nc} and it should be below 0.8 m/s².

Here cant deficiency act as an influencing factor than the speed of vehicle.

4.4.1 Stability Assessment :-

Maximum state derivative at linearization state: joint.st.acc(3): $S_bogie_R.$S_WS2.$J_Ballast = 5.4135511D-06

Mode No. (Pair)	Frequency	Nat. Damping	Undamped Frequency	Real Part
1	0	1	0	-5.969536423489036
2	0	1	0	-5.930637089406798
3	0	1	0	-4.48304041413023
4	0	1	0	-3.863802470959142
5	0	1	0	-2.995841518568169
6	0	1	0	-2.901586663053926
7	0	0	0	-1.052827108413099e-07
8	0	0	0	-1.362425851618148e-14

Fig.4.7 Eigen value calculation test zone 4

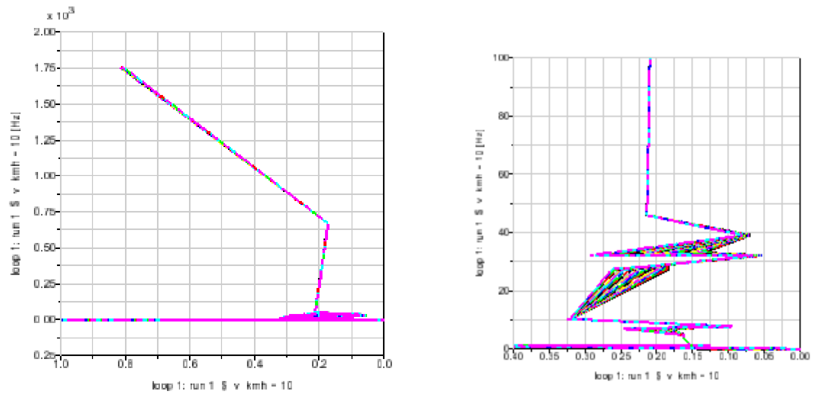
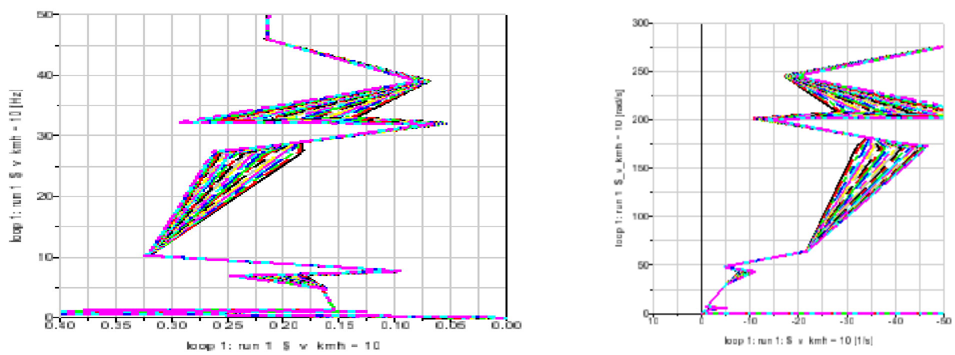


Fig.4.8 Function of Damping vs frequency



Imaginary vs real part (Root locus curve)

Chapter 5

Analysis of Simulation Results According to EN 14363 :-

The simulation results are taken to perform

- filtration on results
- section division
- percentile evaluation
- statistical analysis

to fulfill with the limit values for the assessment quantities.

A low pass filter [20 Hz] was used for running safety and track loading factors and– a band pass filter [0.4-10 Hz] was used for ride characteristics behavior to filter the higher order values and also to follow quasi-static behavior.

5.1 Division on Sections and Percentile Evaluation :-

For the test zone 1, the total distance (10 km) of the track is divided in more than 30 sections as per the standard. In our case the test zone was divided in 40 sections making each section length to be 250 m. The results then analyzed in each divided section and calculated the percentile evaluation (differs for each assessment quantities).

For the test zone 2, the total distance (10.04 km) of the track is distributed into 5 curve sections (left- and right-hand curves). Each circular curve is divided in 5 sections of length 1250 m making each section length to be 250 m. The results then analyzed in each divided section and calculated the percentile evaluation (differs for each assessment quantities).

For the test zone 3, the total distance (7.80 km) of the track is distributed into 5 curve sections (left- and right-hand curves). Each circular curve is divided in 10 sections of length 1000 m making each section length to be 100 m. The results then analyzed in each divided section and calculated the percentile evaluation (differs for each assessment quantities).

For the test zone 4, the total distance (5.13 km) of the track is distributed into 5 curve sections (left- and right-hand curves). Each circular curve is divided in 5 sections of length 350 m making each section length to be 70 m. The results then analyzed in each divided section and calculated the percentile evaluation (differs for each assessment quantities) [3].

The frequency values $y(h_j)$ is determined for each frequency distribution.

- ***y(h1)***, frequency of cumulative curve ***h1*** = 0,15 %
- ***y(h0)***, frequency of cumulative curve ***h0*** = 50,0 %;
- ***y(h2)***, frequency of cumulative curve ***h2*** = 99,85 %.

5.2 Results on Statistical Evaluation :-

The evaluation based on statistical approach were performed in order to obtain consistent approach to general reliable results on assessment values and creates the pre-requisites for the acceptance of vehicle.

Statistical evaluation is carried out separately for each random sample. The confidence level Y(PA) is increased to 99 % for calculating the running safety, track loading, ride characteristics parameters.

The estimated maximum value is calculated from mean value and standard deviation [1].

$$\mathbf{Y(PA)max = y + k\, sy}$$

K = 3 for running safety

K= 2.2 for track loading and ride characteristics

Here Y/Q is evaluated for leading wheelset on each bogie. It is also calculated in respect to curve conditions also (i.e. right-hand curve – left wheel ; left hand curve – right wheel)

5.2.1 Test Zone 1 :-

It is not necessary to evaluate the Q forces for track loading characteristics according to EN 14363. The Running safety and ride characteristics results are analyzed and shown below.

Bogie Front Wheelset 1 :-

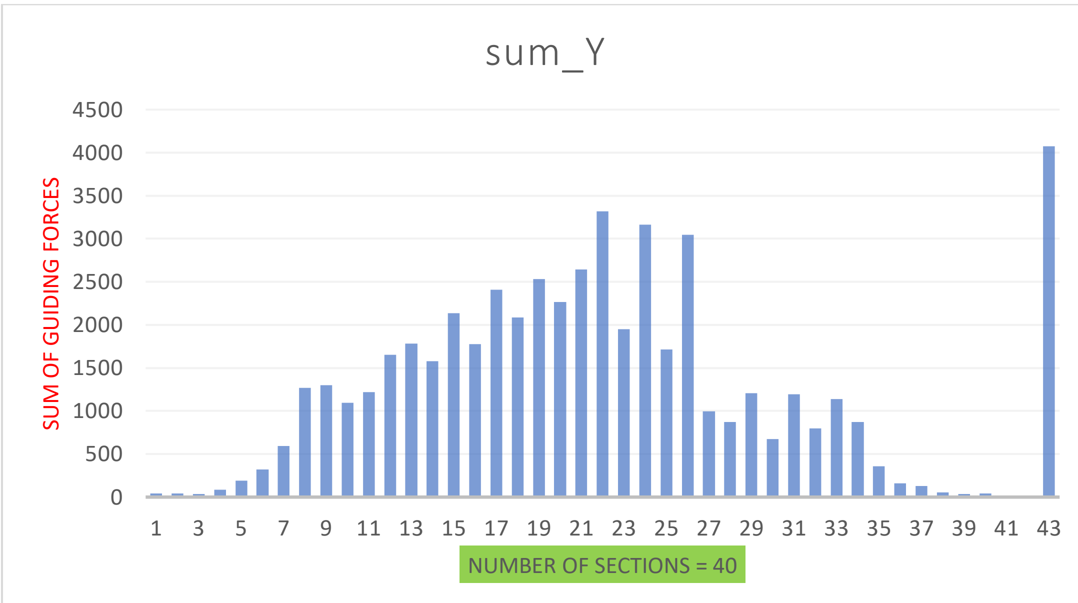


Fig.5.1 Sum of lateral forces (Running safety)

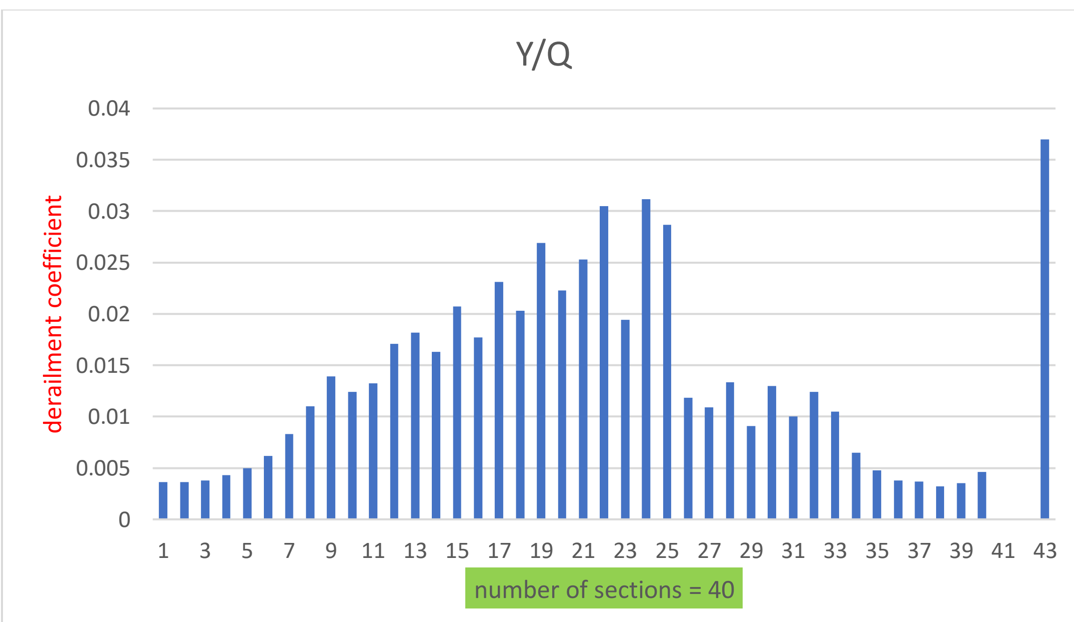


Fig.5.2 Derailment coefficient (Running safety)

Bogie Front Wheelset 2 :-

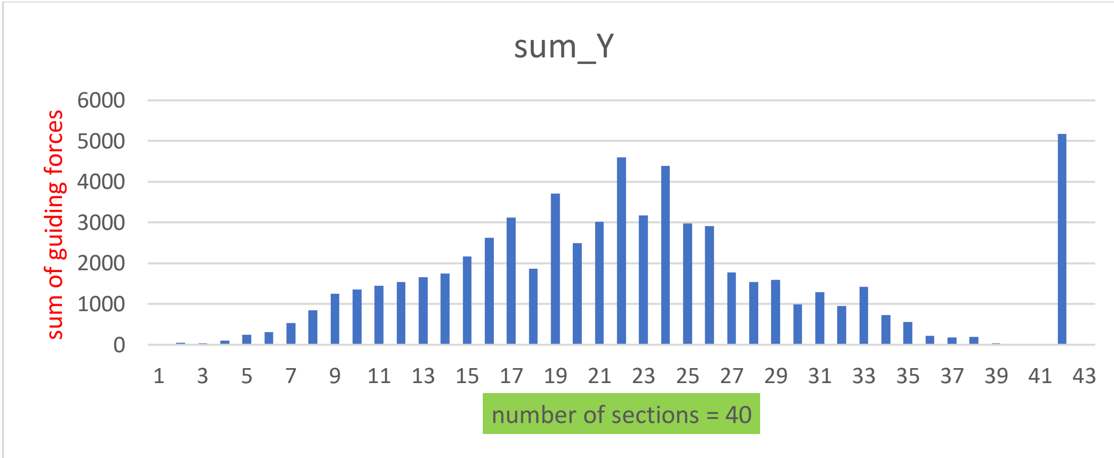


Fig.5.3 Sum of guiding forces (Running safety)

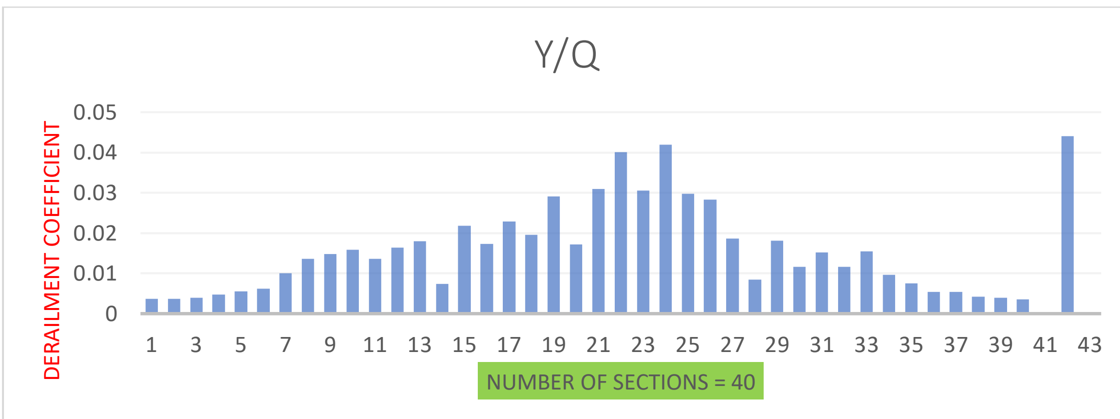


Fig.5.4 Derailment coefficient (Running safety)

Bogie Rear Wheelset 1 :-

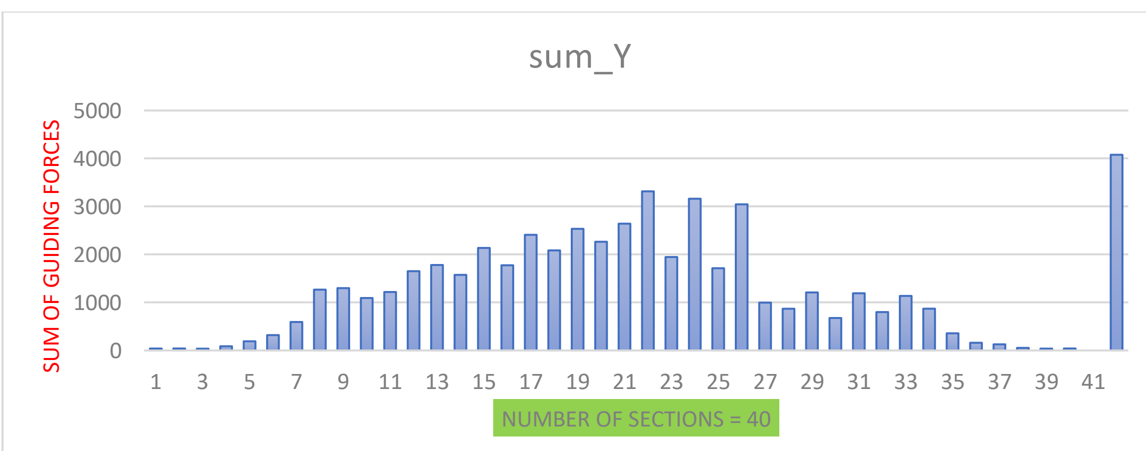


Fig.5.5 Sum of lateral forces (Running safety)

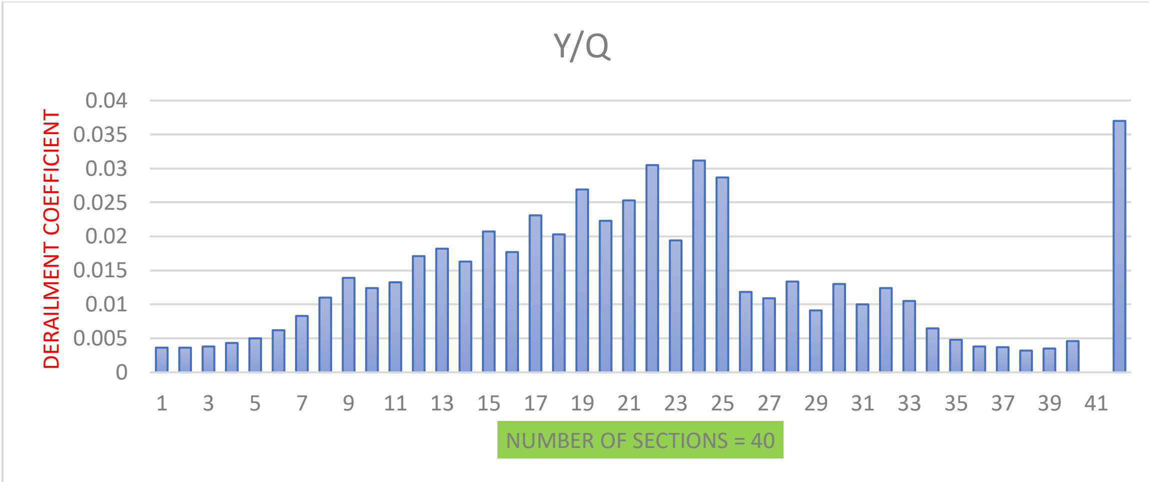


Fig.5.6 Derailment coefficient (Running safety)

Bogie Rear Wheelset 2 :-

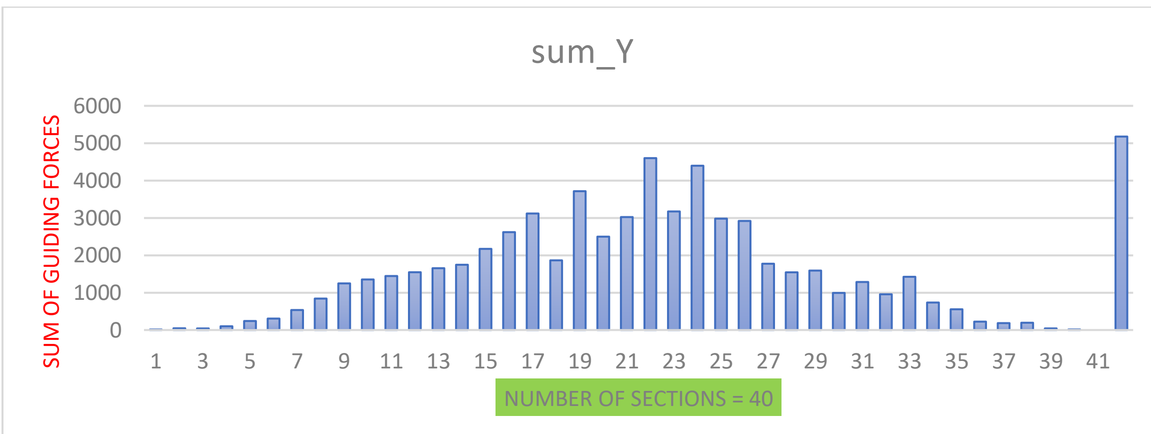


Fig.5.7 Sum of lateral forces (Running safety)

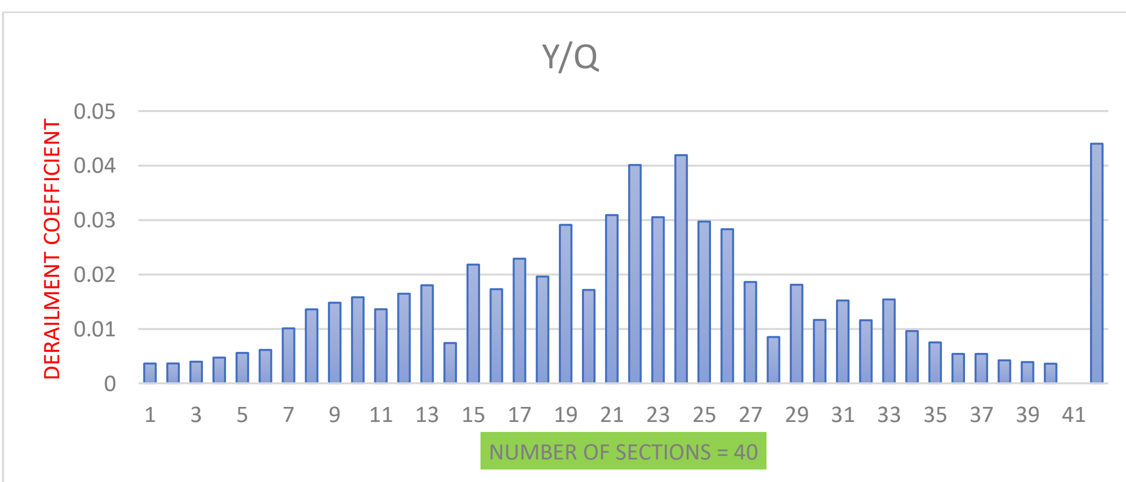


Fig.5.8 Derailment coefficient (Running safety)

Car-Body Acceleration :-

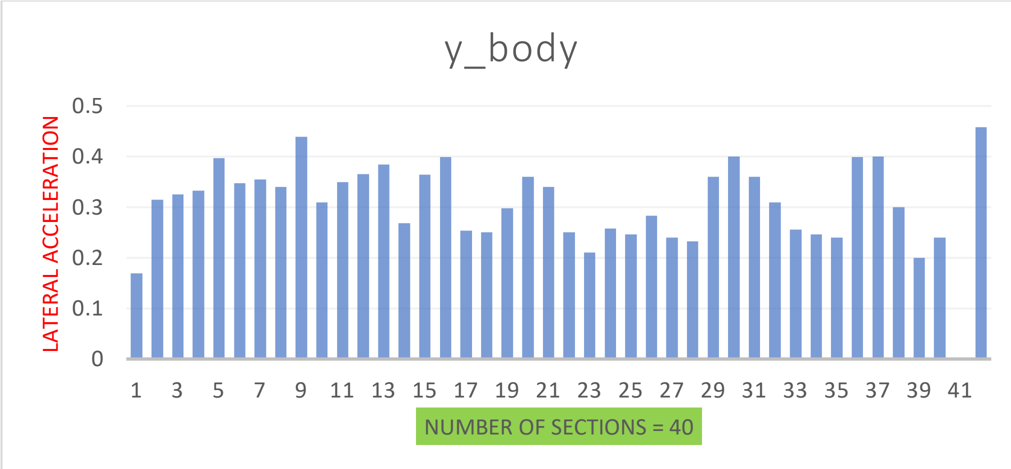


Fig.5.9 lateral acceleration

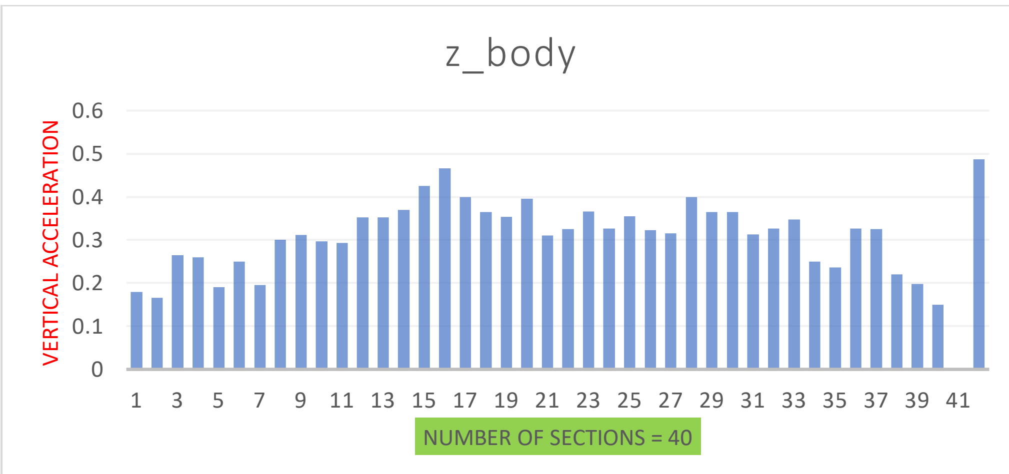


Fig.5.10 Vertical acceleration

NOTE :- The statistical evaluation was performed with one value of each section with one dimensional analysis and the final estimated value is compared with the limit value.

5.2.2 Test Zone 2 :-

Bogie Front Wheelset 1 :-

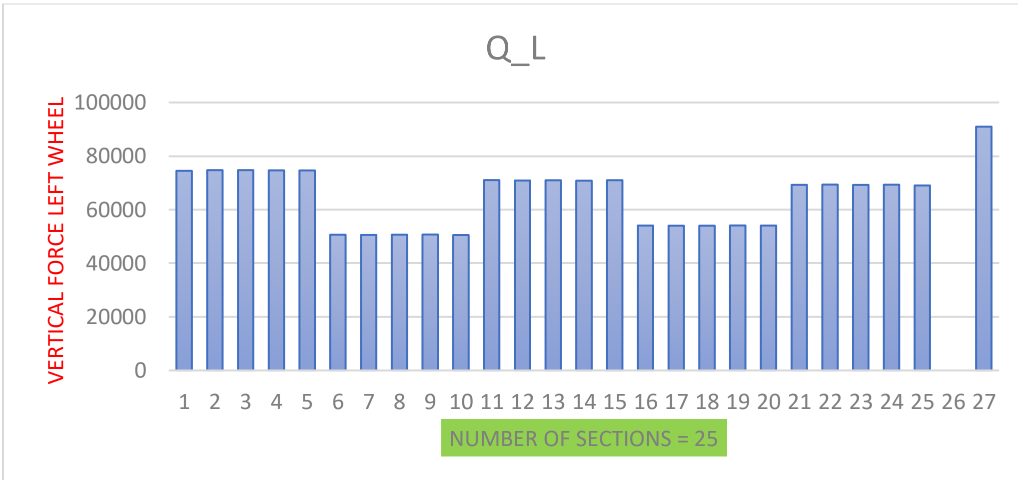
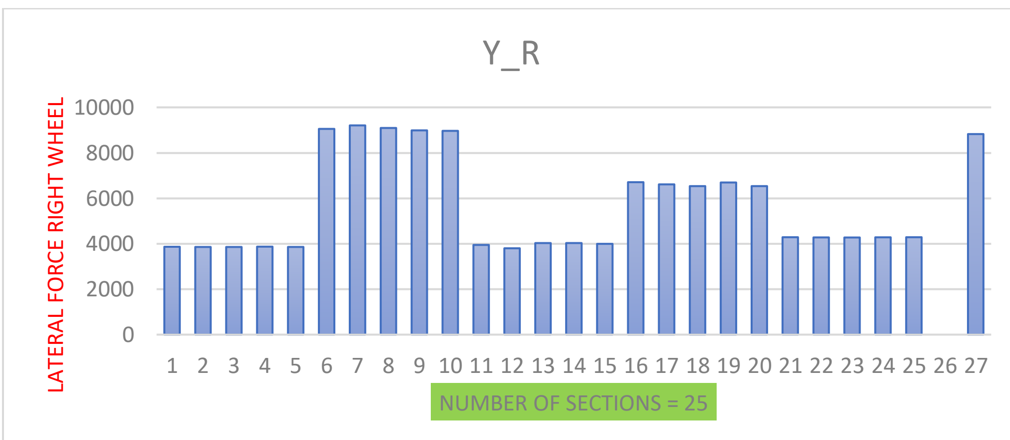


Fig.5.11 Vertical force Q (Right & left wheel)



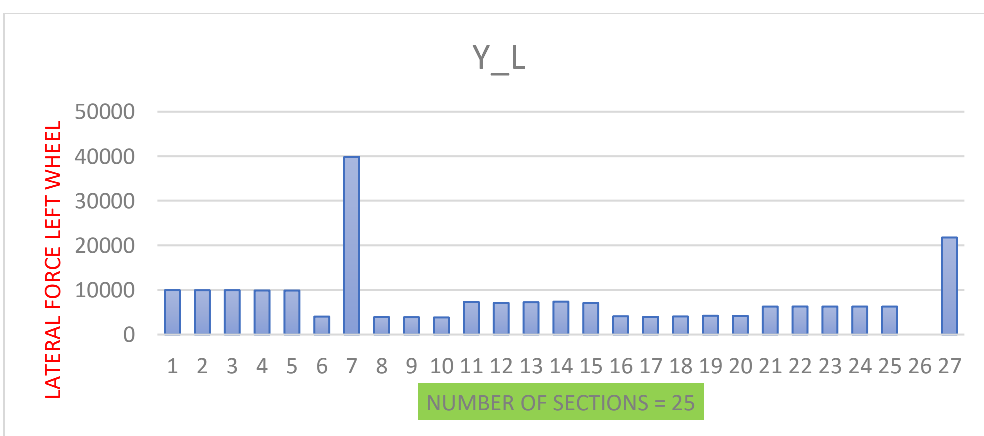


Fig.5.12 Lateral force Y (Right & Left wheel)

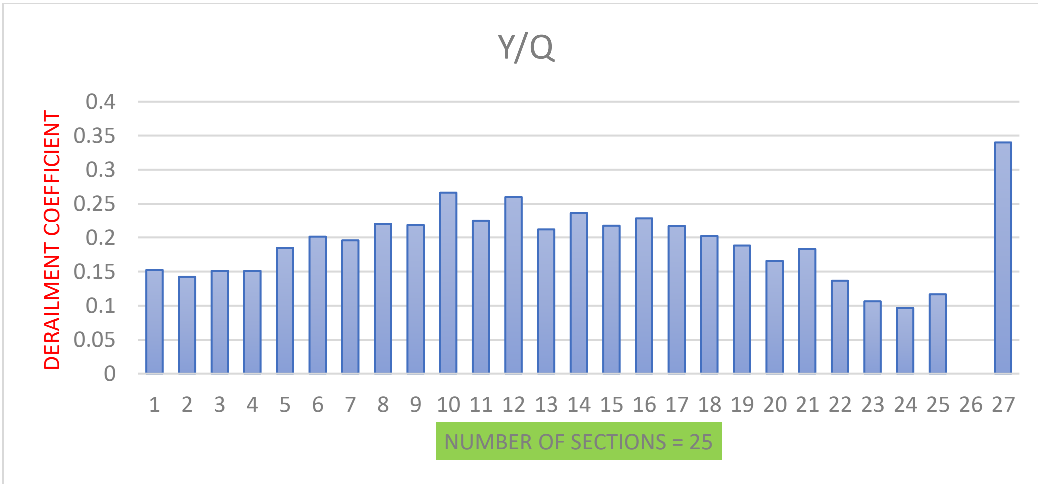


Fig.5.13 Derailment coefficient (Running safety)

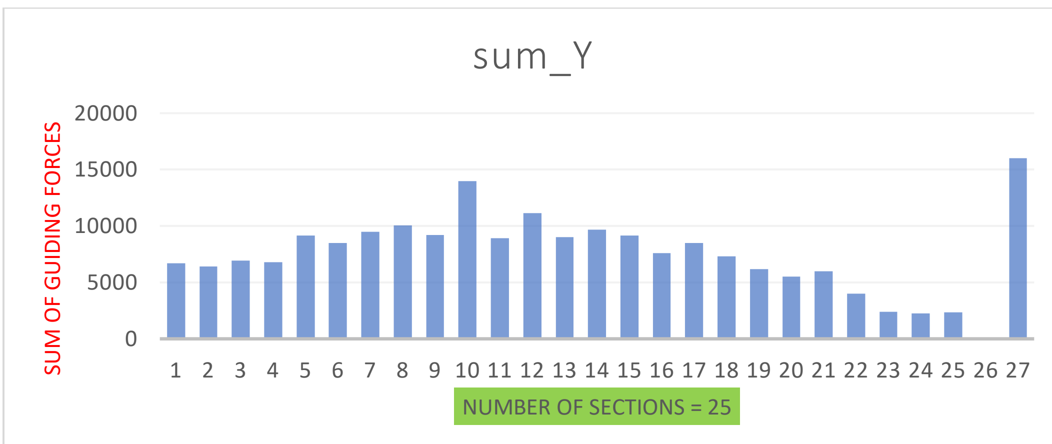
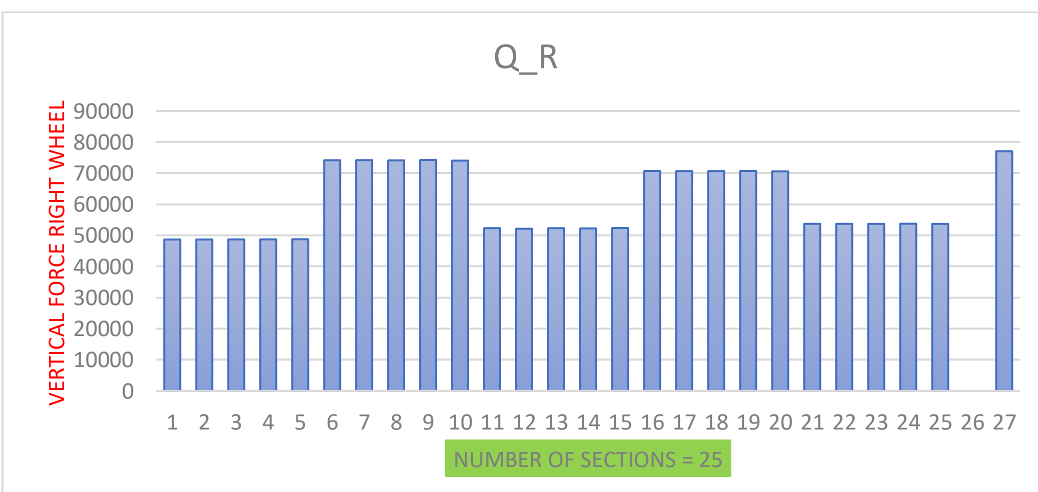


Fig.5.14 Sum of lateral forces (Running safety)

Bogie Front Wheelset 2 :-



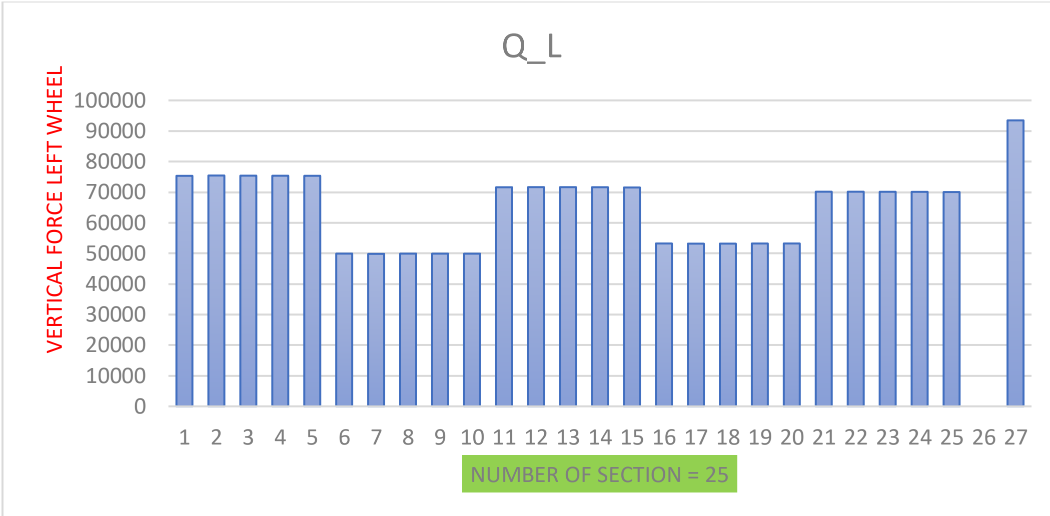
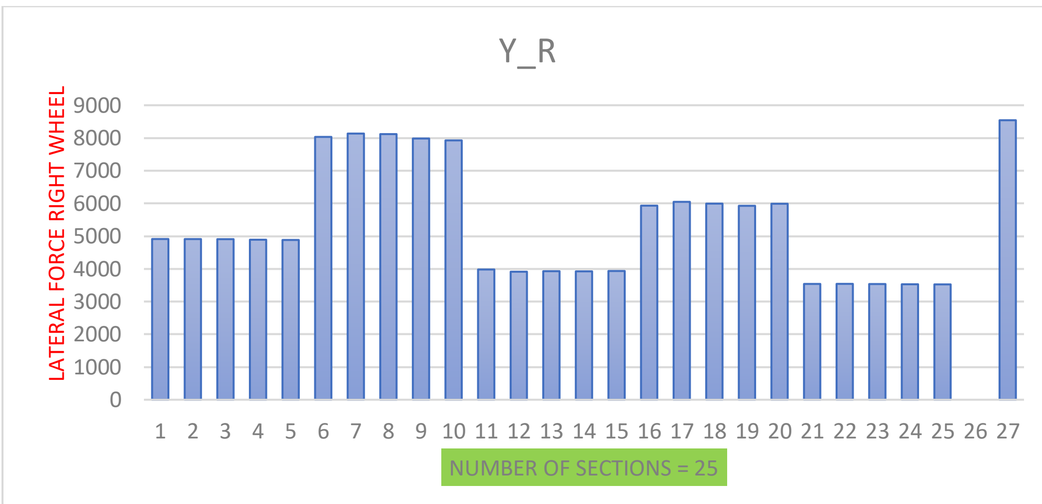


Fig.5.15 Vertical forces (Right and left wheel)



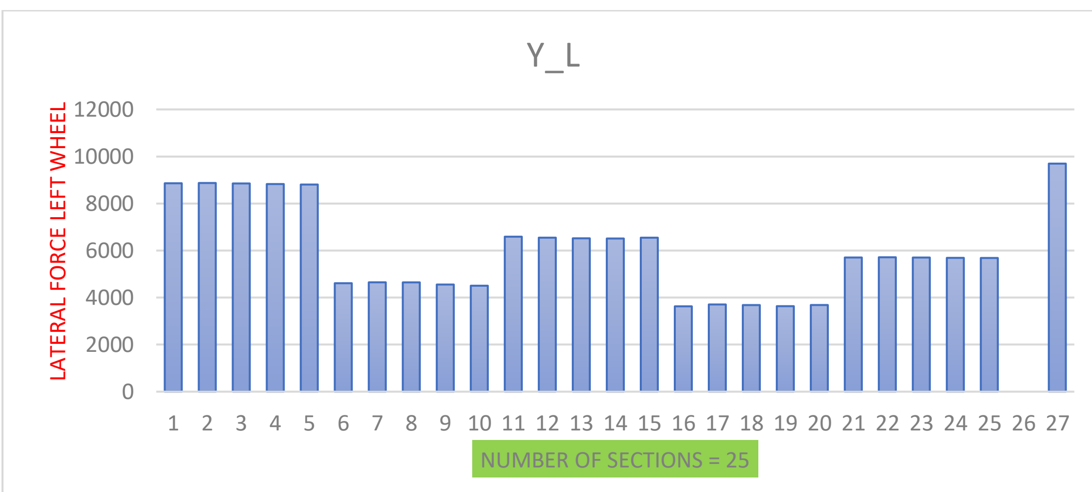


Fig.5.16 Lateral force Y (Right and Left wheel)

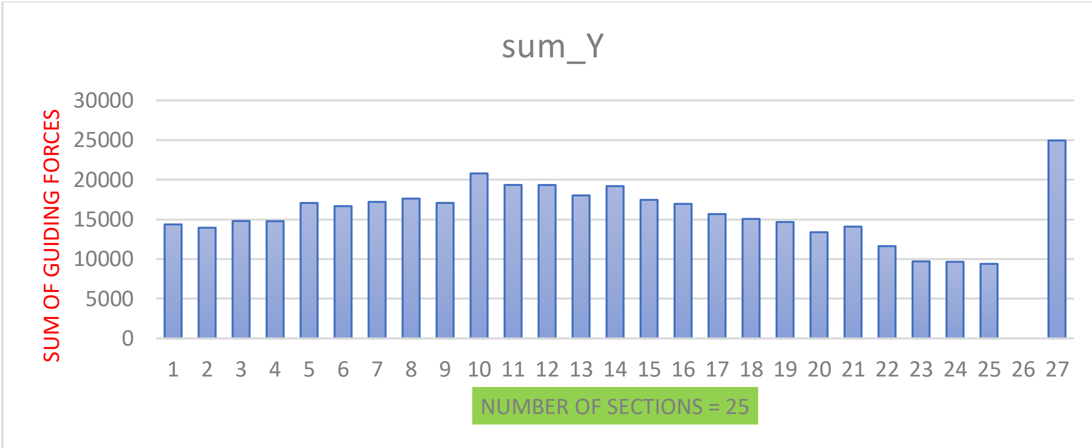
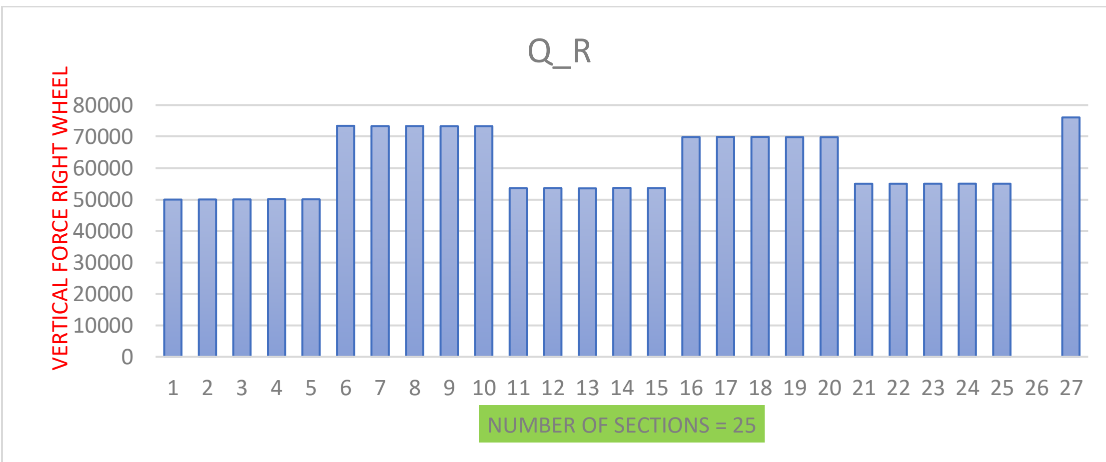


Fig.5.17 Sum of lateral forces (Running safety)

Bogie Rear Wheelset 1 :-



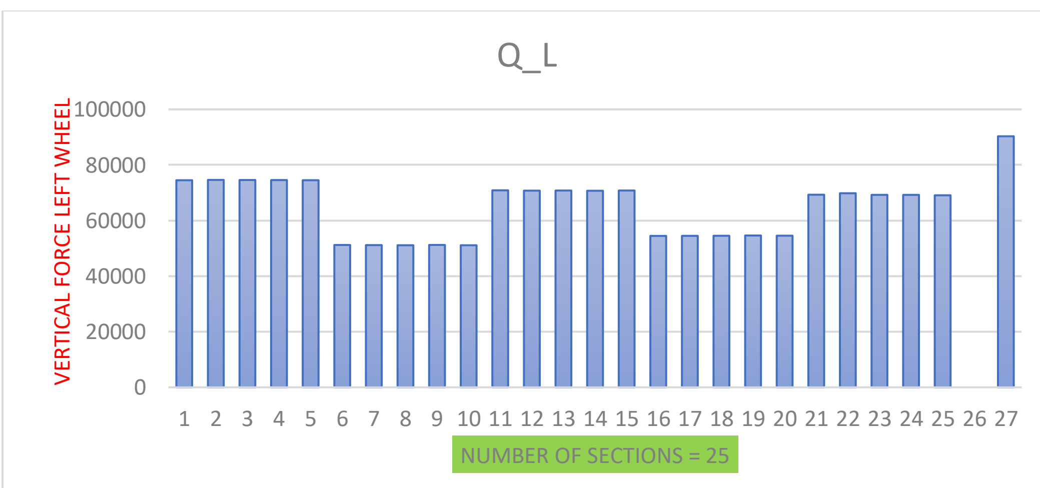
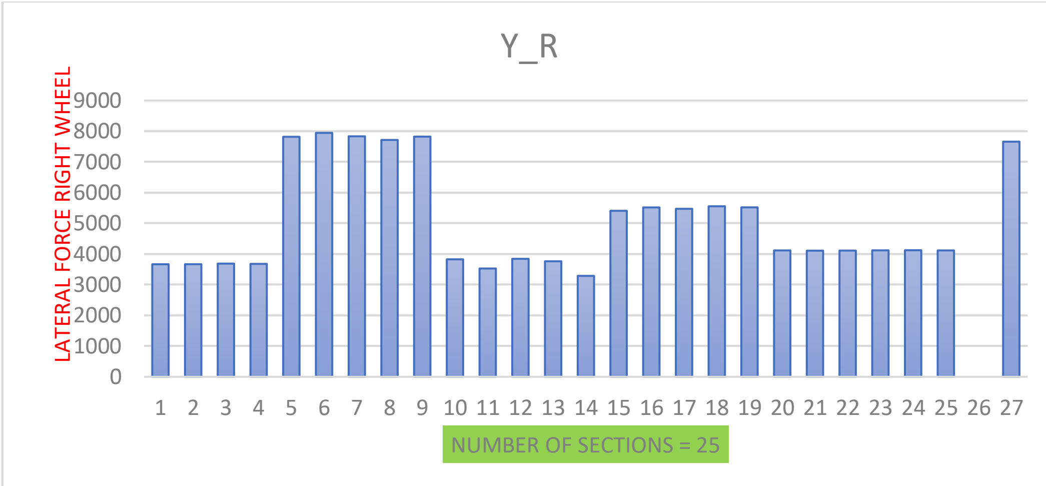


Fig.5.18 Vertical force Q (Right & left wheel)



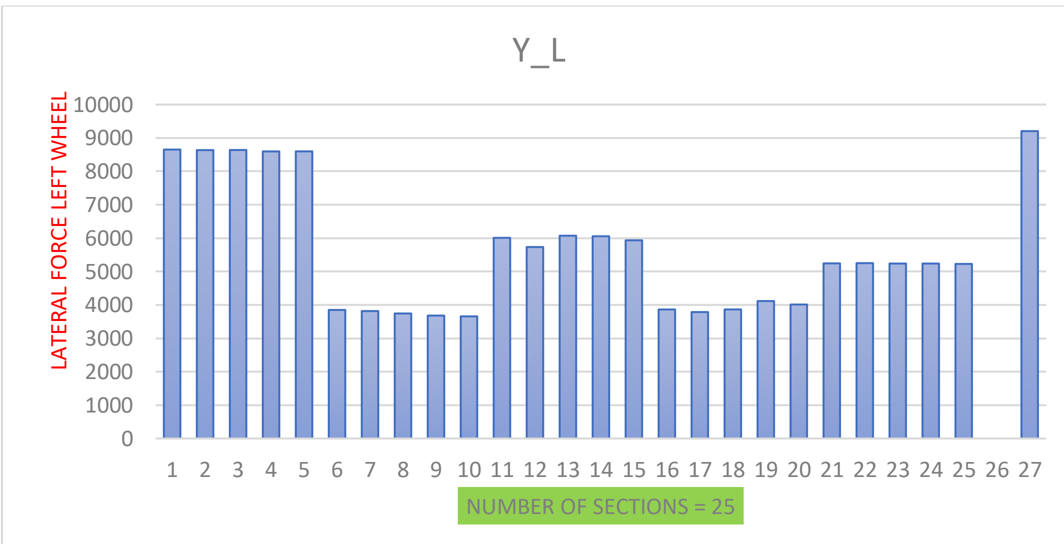


Fig.5.19 Lateral force Y (Right and left wheel)

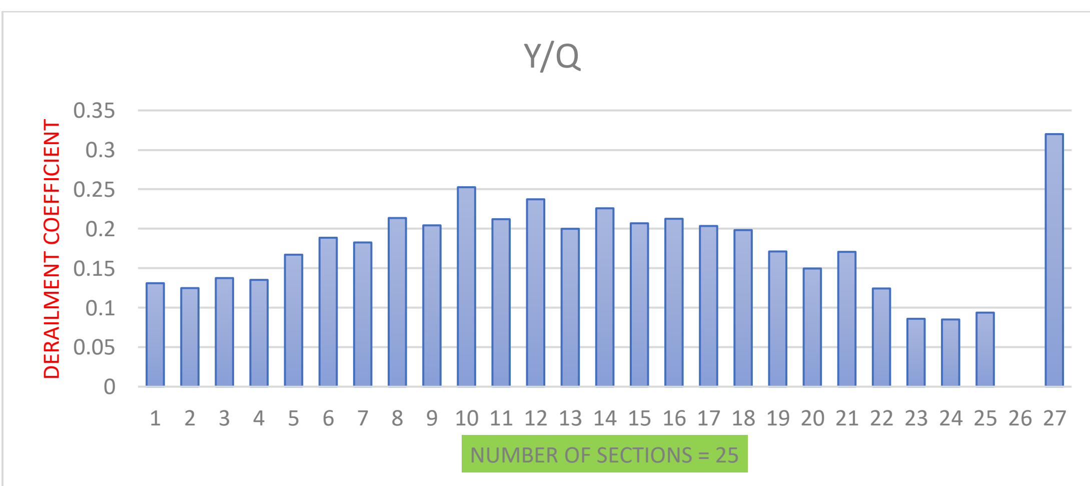


Fig.5.20 Derailment coefficient (Running safety)

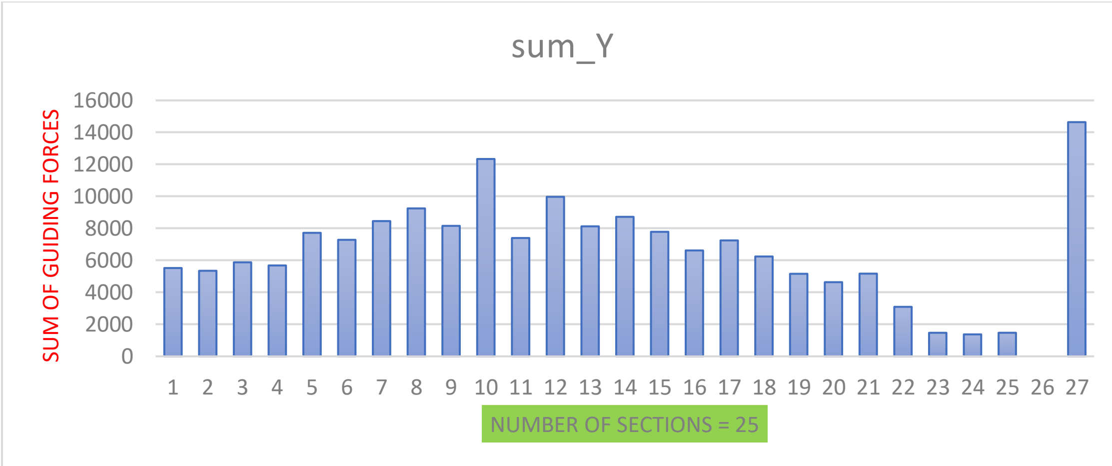
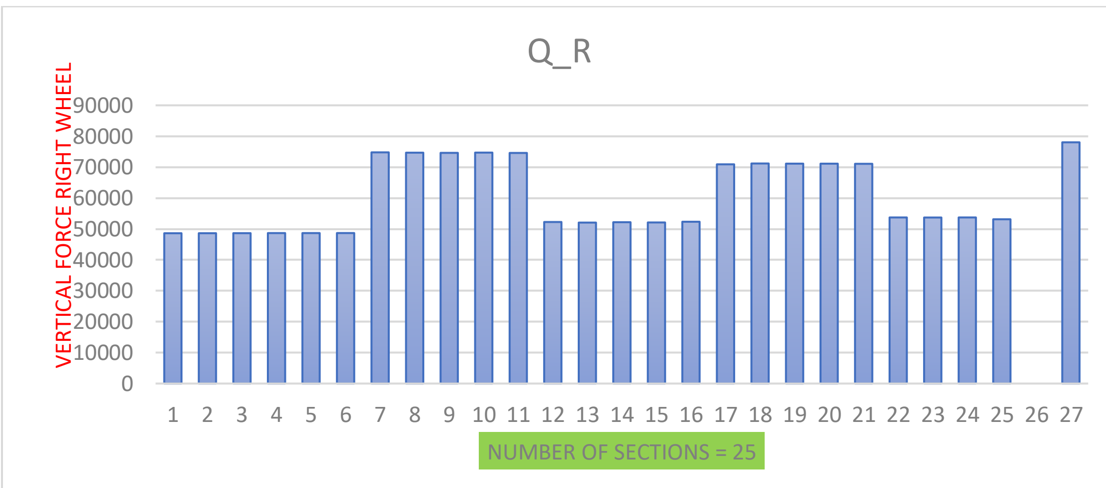


Fig.5.21 Sum of lateral forces (Running safety)

Bogie Rear Wheelset 2 :-



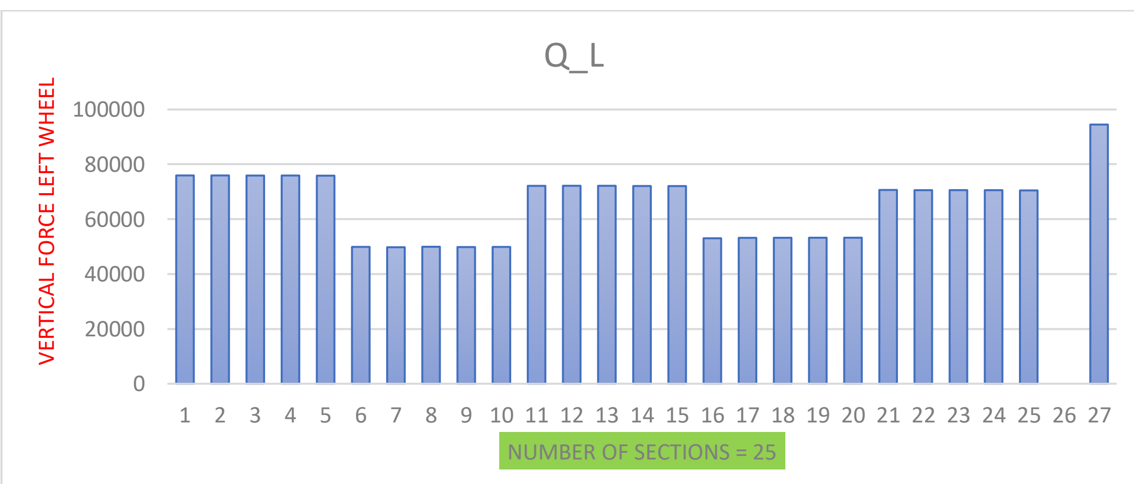
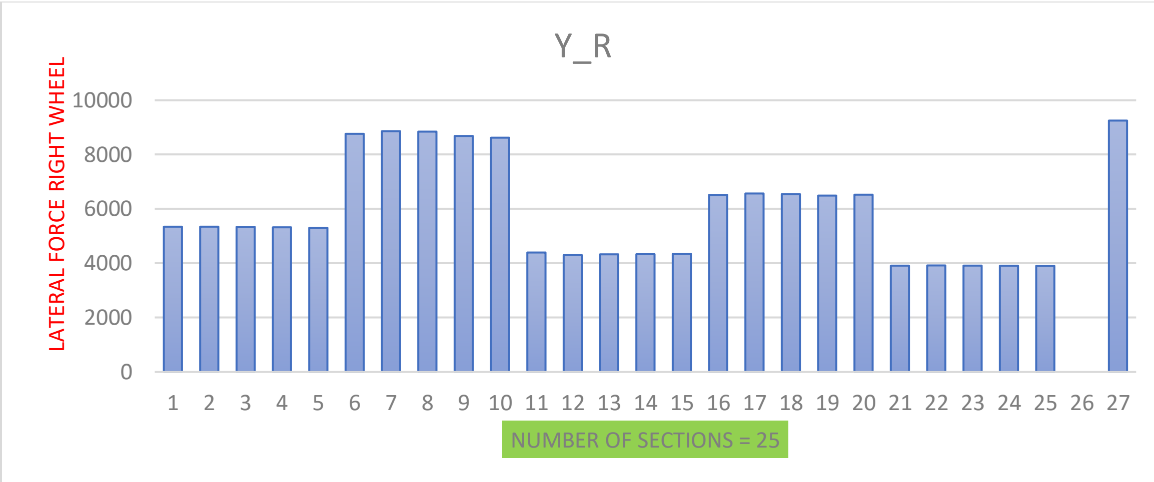


Fig.5.22 Vertical forces (Right & Left wheel)



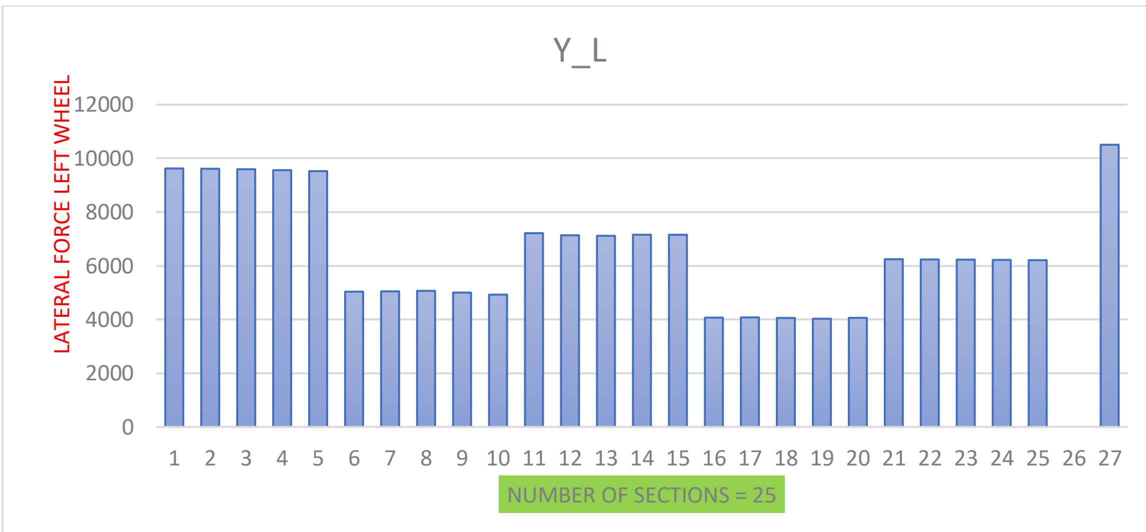


Fig.5.23 Lateral force Y (Right & Left wheel)

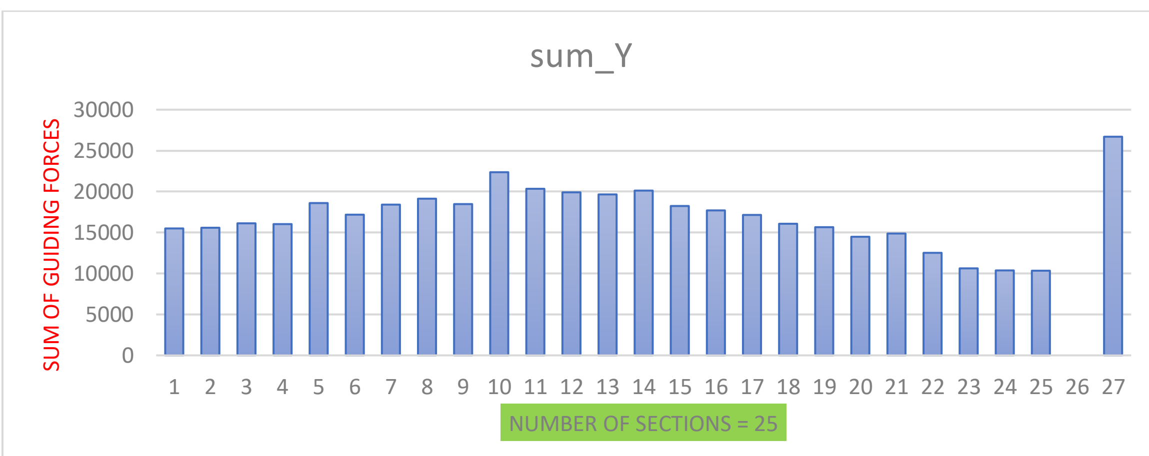


Fig.5.24 Sum of lateral forces (Running safety)

CAR-BODY ACCELERATIONS :-

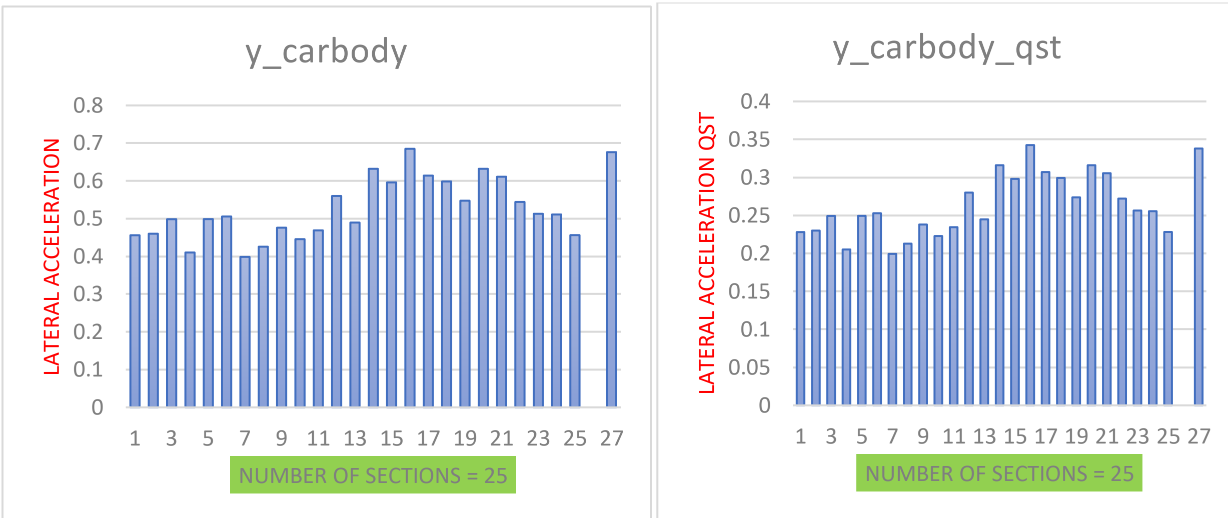


Fig.5.25 Lateral acceleration (Ride characteristics)

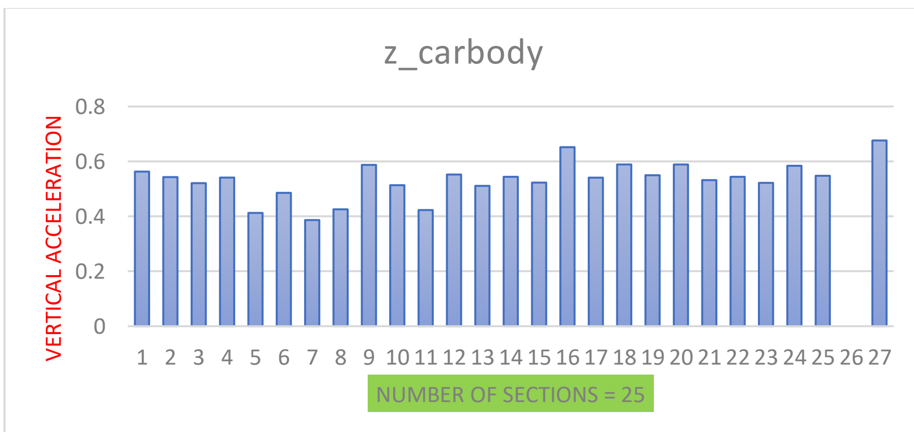
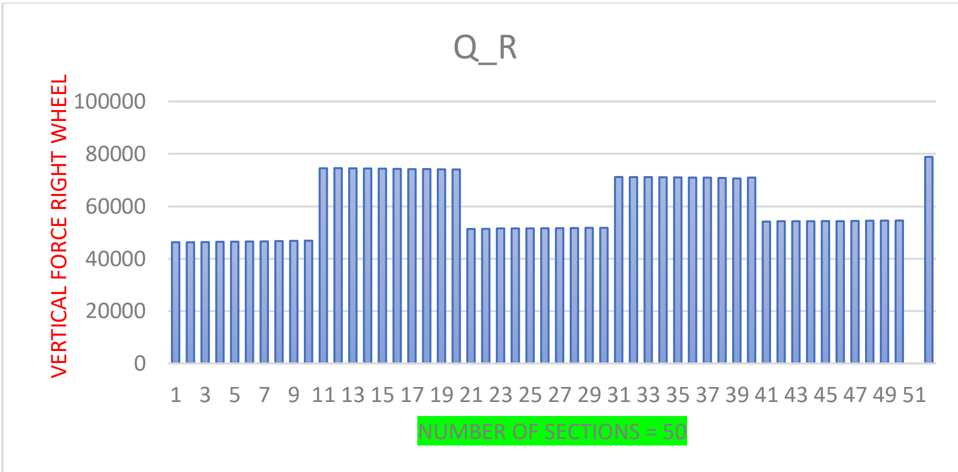


Fig.5.26 Vertical acceleration (Ride characteristics)

5.3.3 Test Zone 3 :-

Bogie Front Wheelset 1 :-



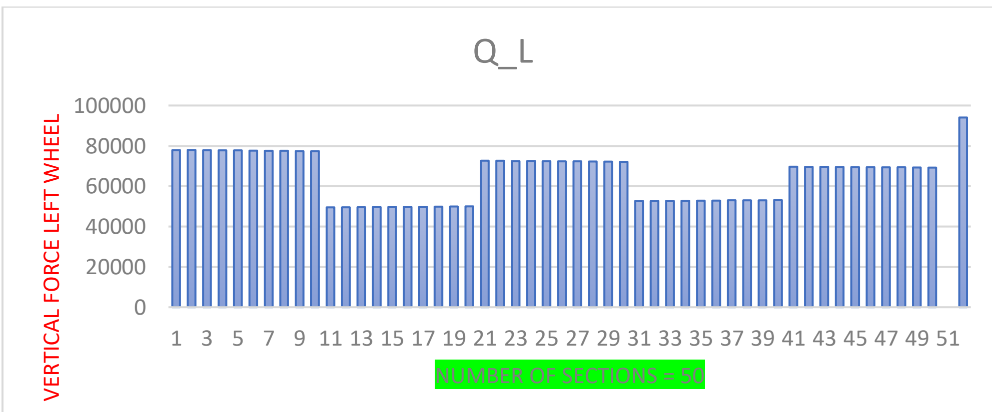
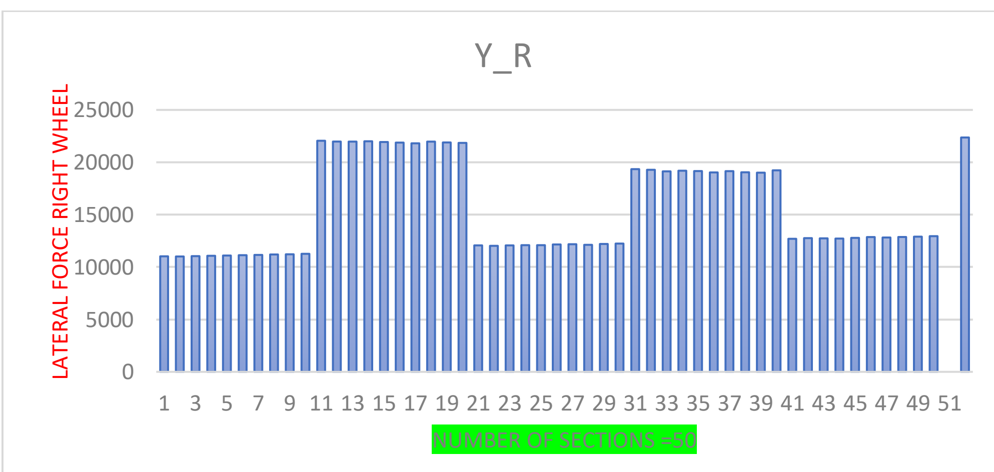


Fig.5.27 Vertical forces Q (Right & Left wheel)



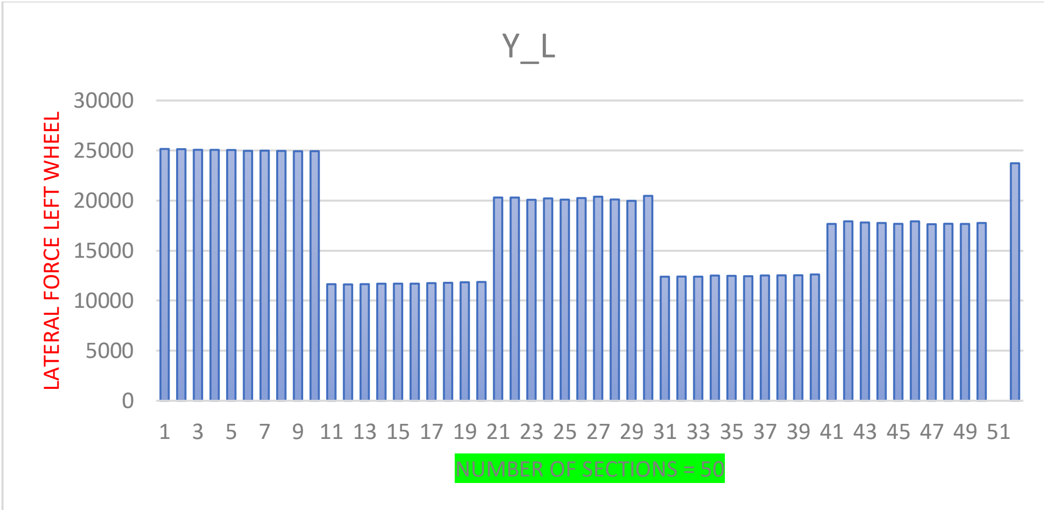


Fig.5.28 Lateral force Y (Right & Left wheel)

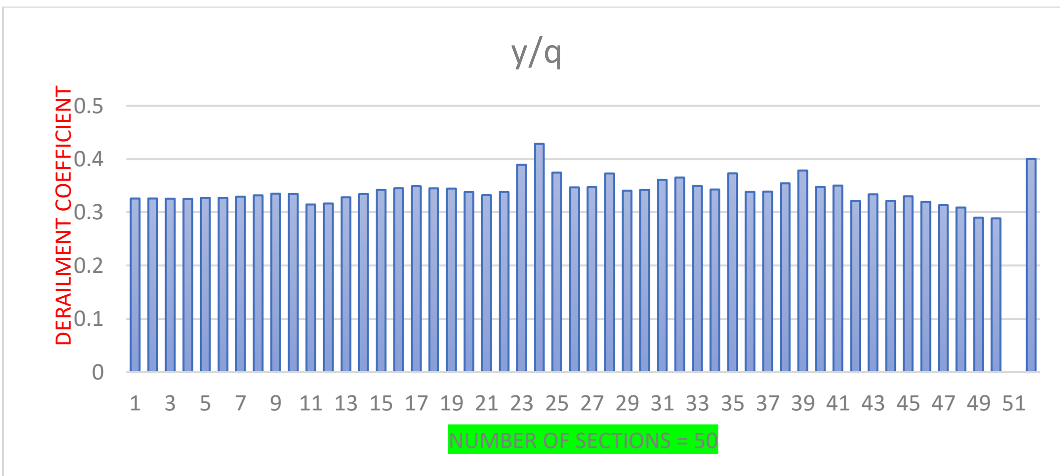


Fig.5.29 Derailment coefficient (Running safety)

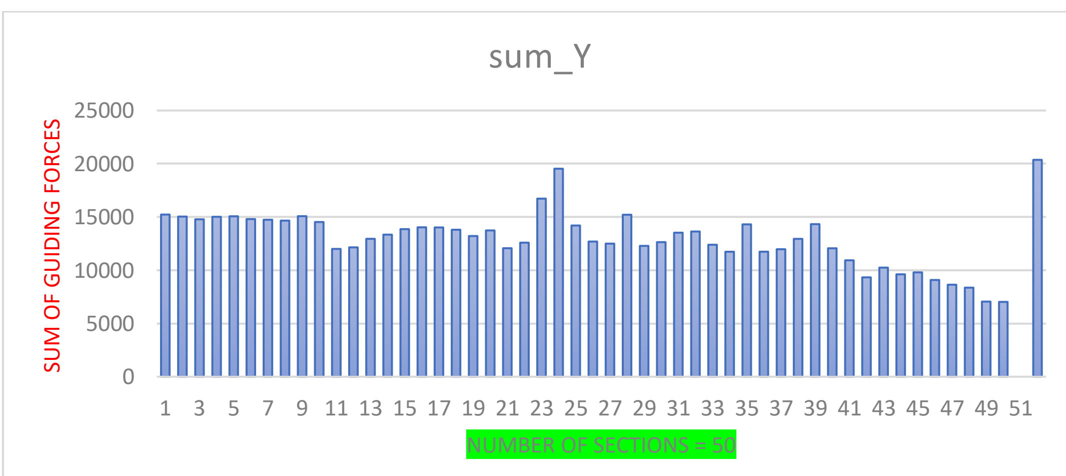
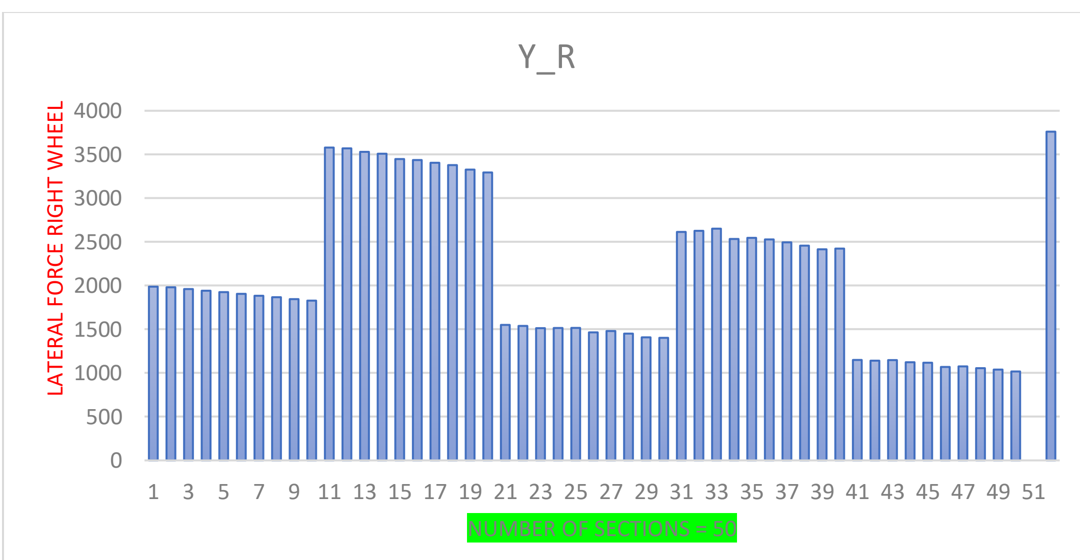


Fig.5.30 Sum of lateral forces (Running safety)

Bogie Front Wheelset 2 :-

Fig.5.31 Vertical force Q (Right & Left wheel)



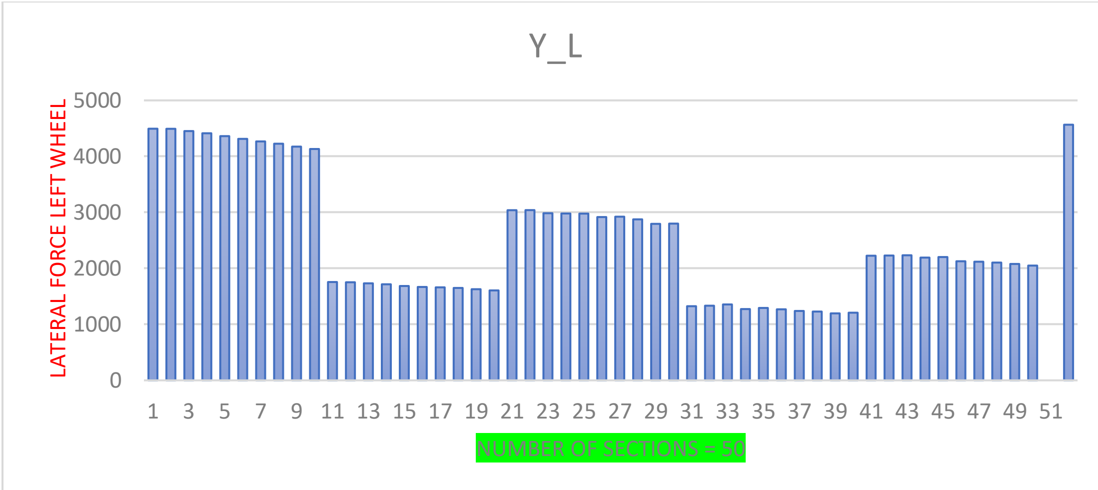


Fig.5.32 Lateral force Y (Right & Left wheel)

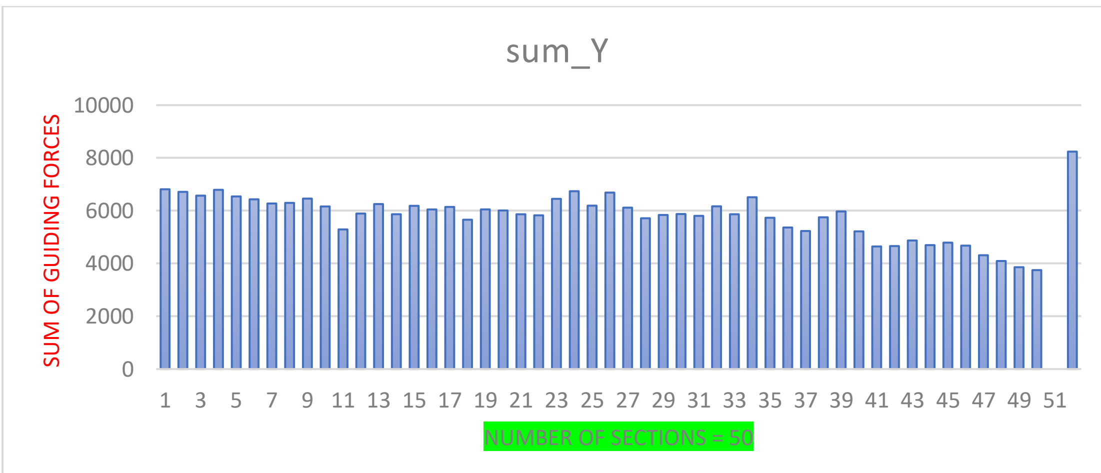
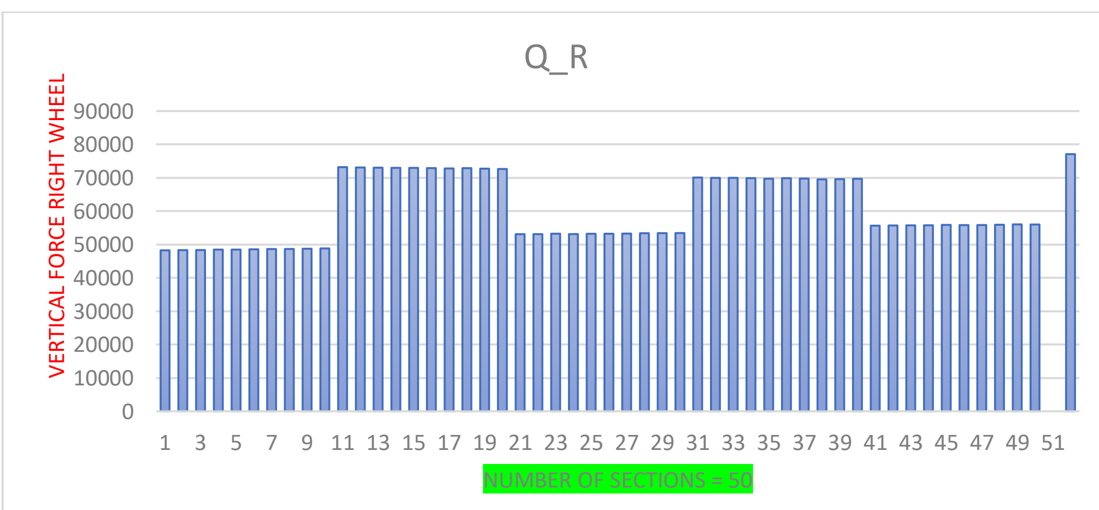


Fig.5.33 Sum of lateral forces (Running safety)

BOGIE REAR WHEELSET 1 :-



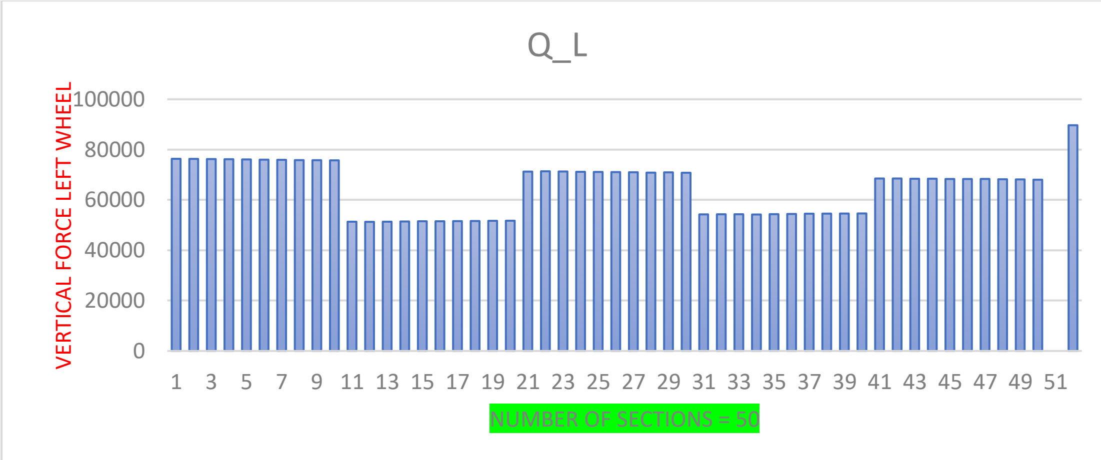
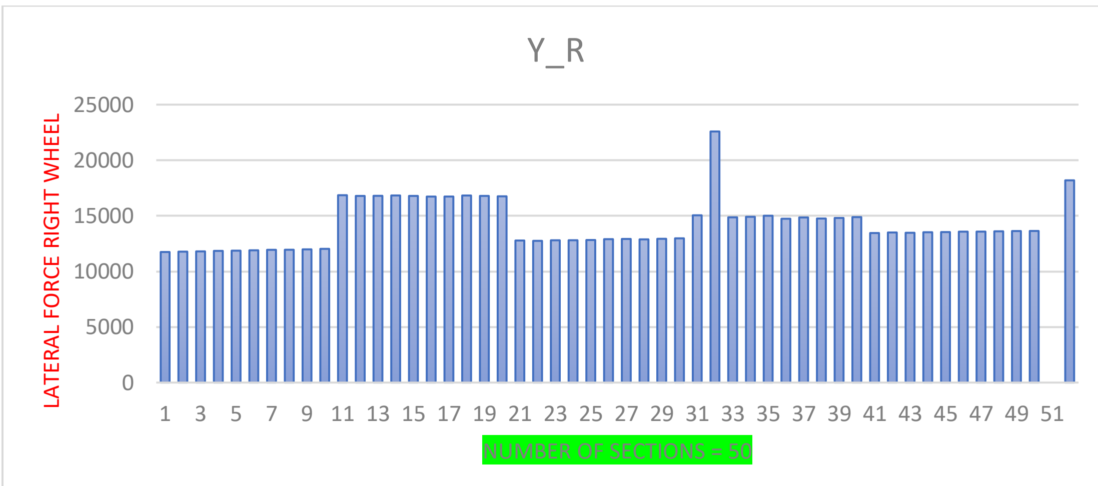


Fig.5.34 Vertical force Q (Right & Left wheel)



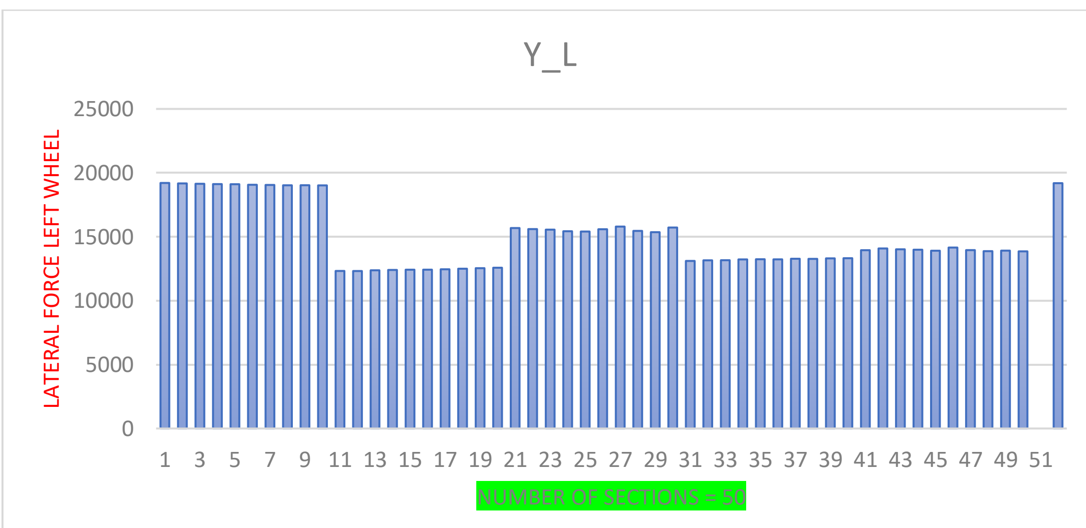


Fig.5.35 Lateral force (Right & Left wheel)

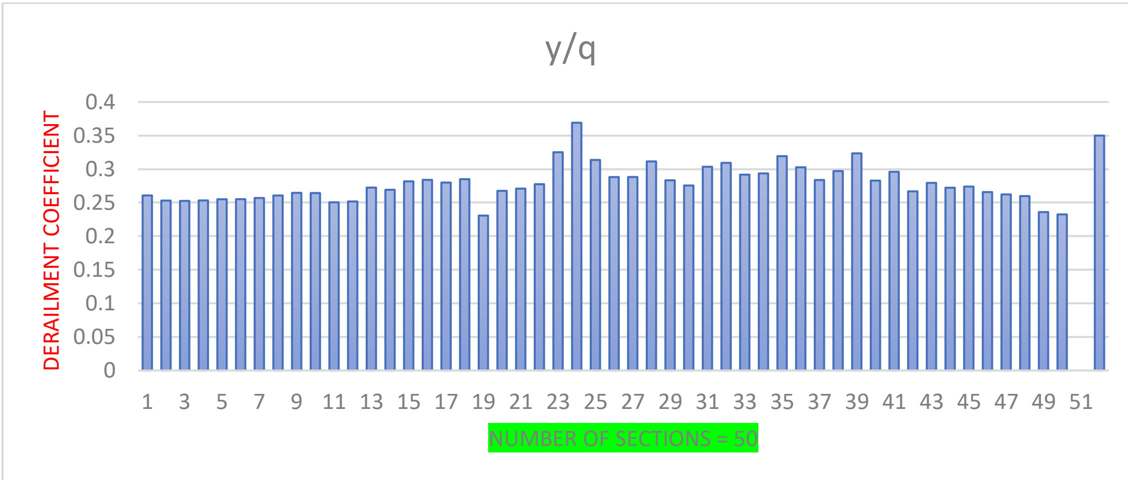


Fig.5.36 Derailment coefficient (Running safety)

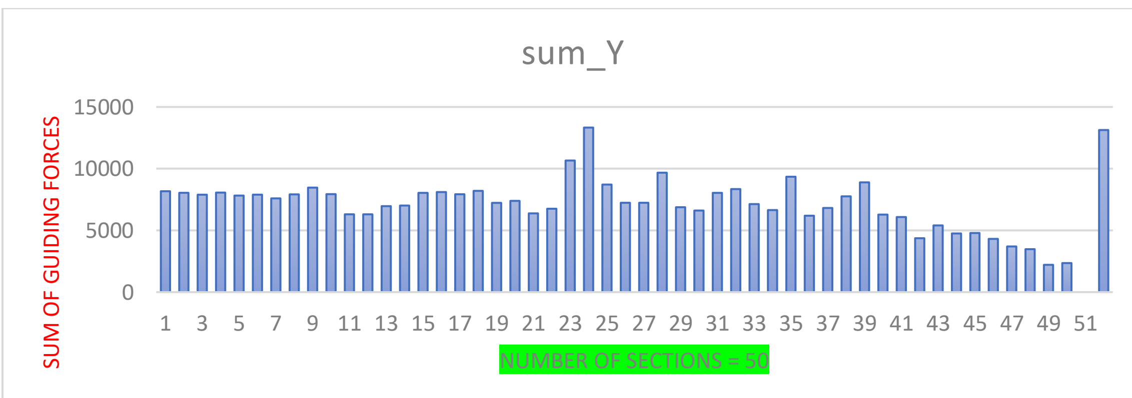
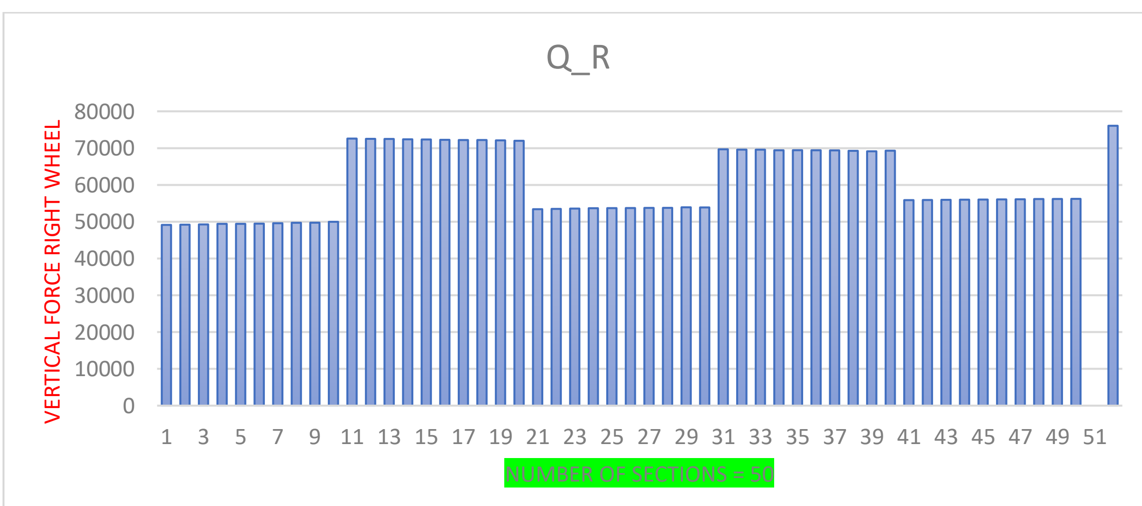


Fig.5.37 Sum of lateral forces

Bogie Rear Wheelset 2 :-



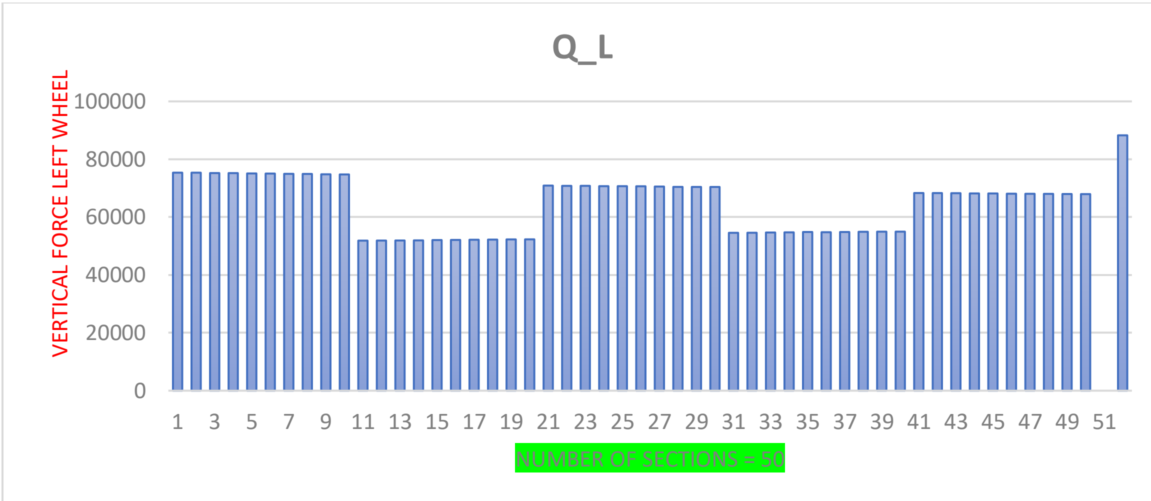


Fig.5.38 Vertical force Q (Right & Left wheel)

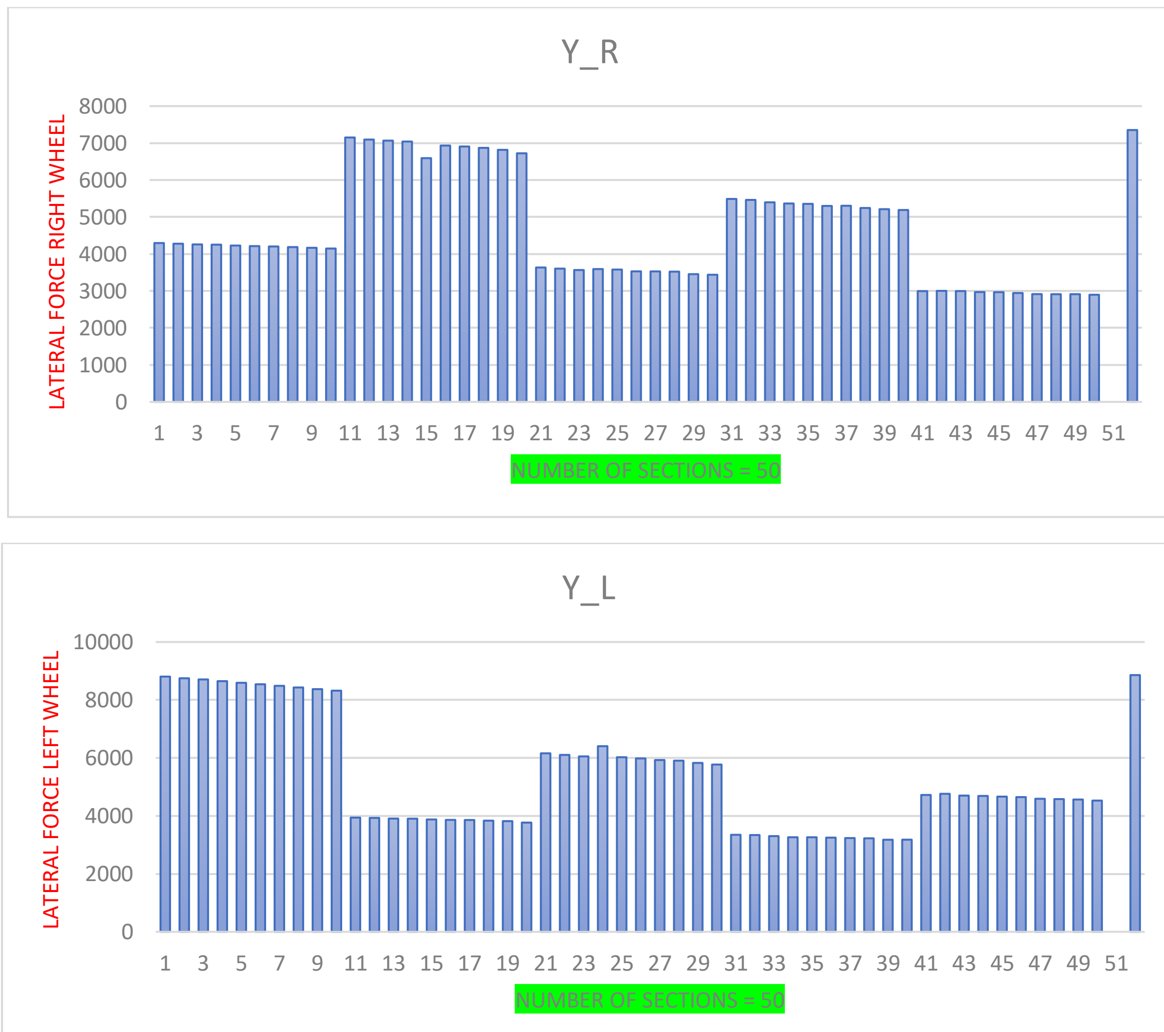


Fig.5.39 Lateral force Y (Right & Left wheel)

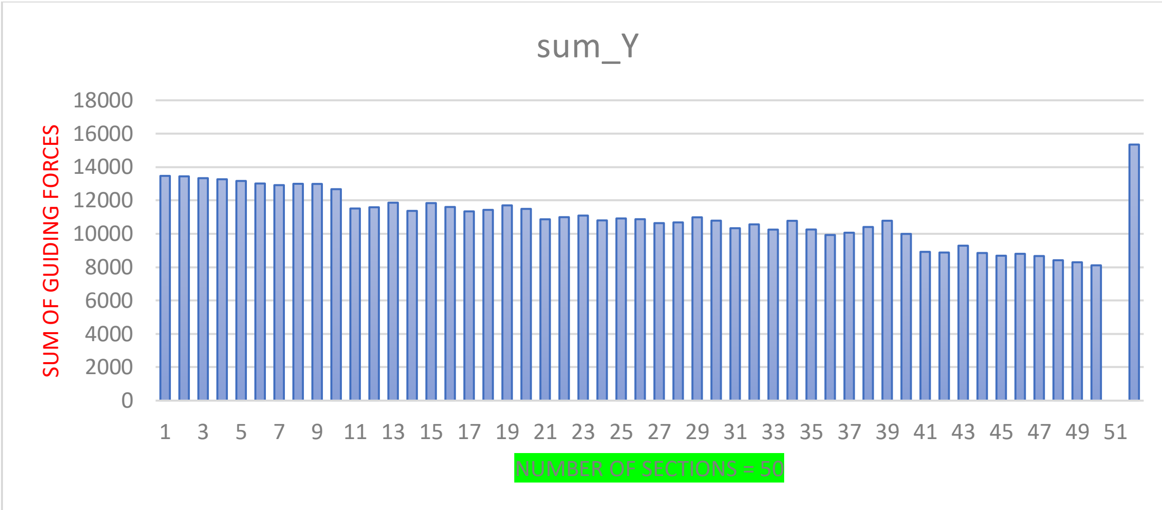
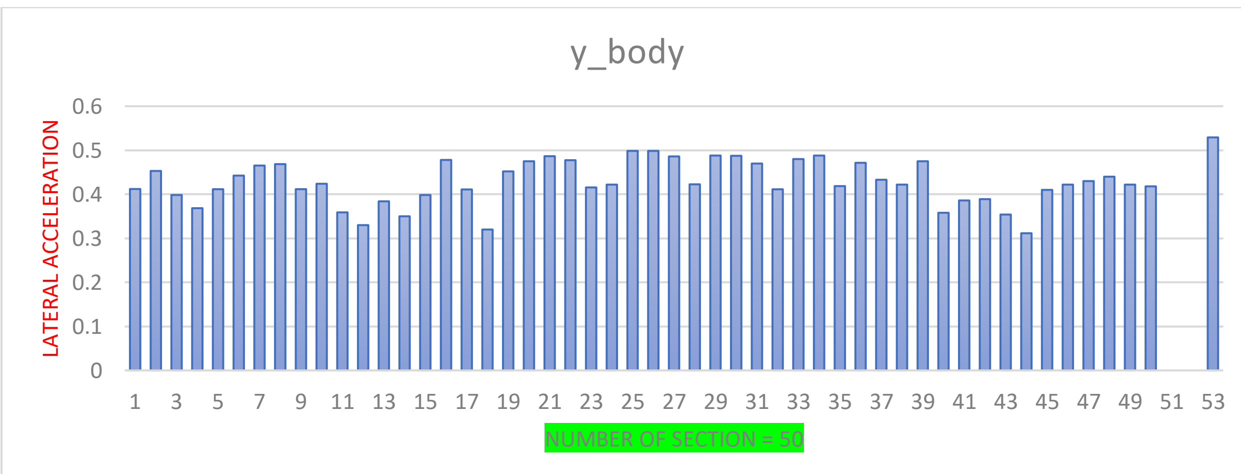


Fig.5.40 Sum of lateral forces (Running safety)

CAR-BODY ACCELERATION :-



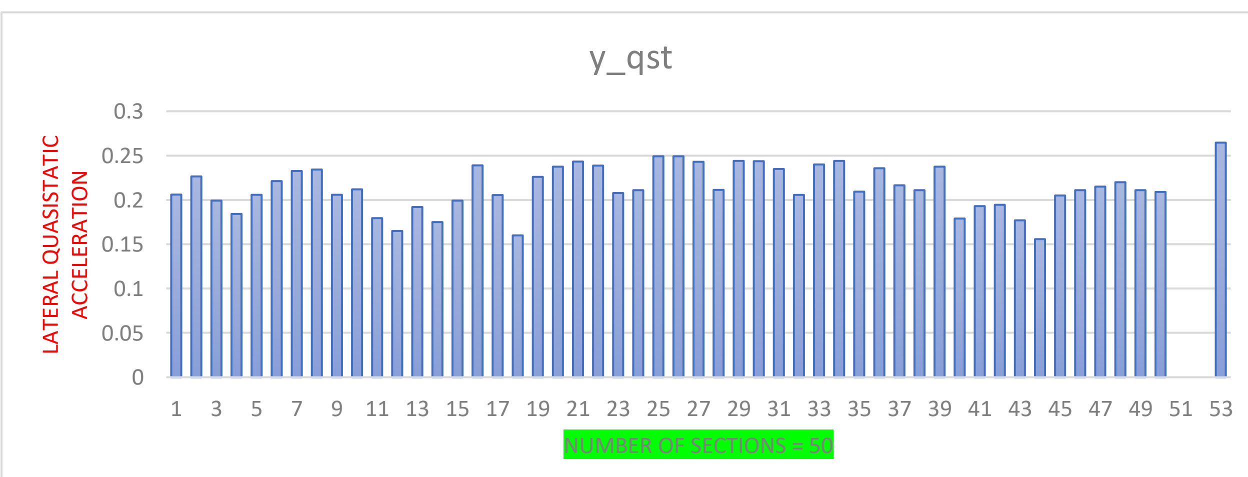


Fig.5.41 Lateral acceleration

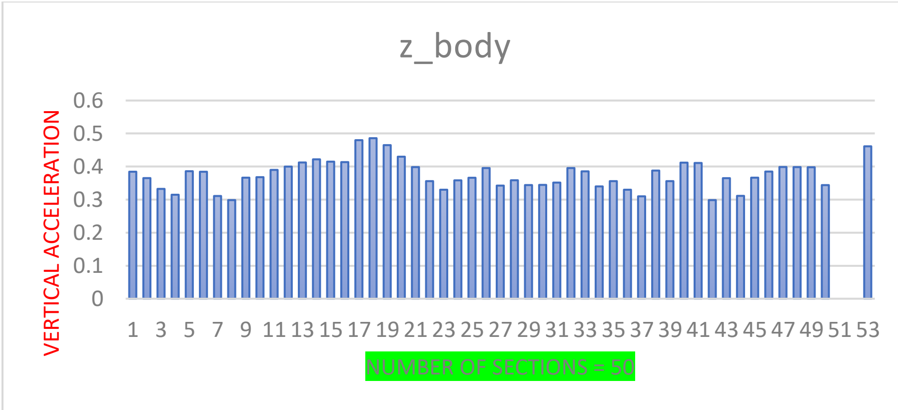
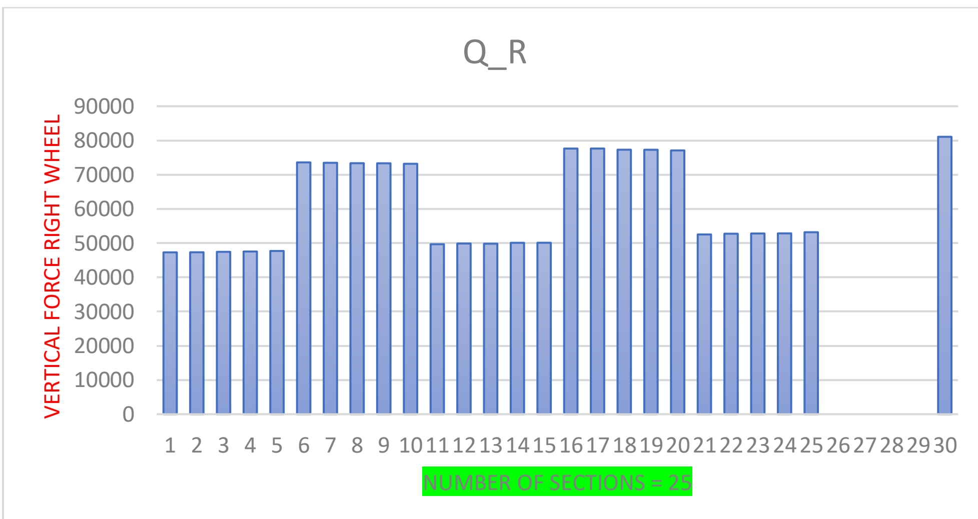


Fig.5.42 Vertical acceleration

5.3.4 Test Zone 4 :-

Bogie Front Wheelset 1 :-



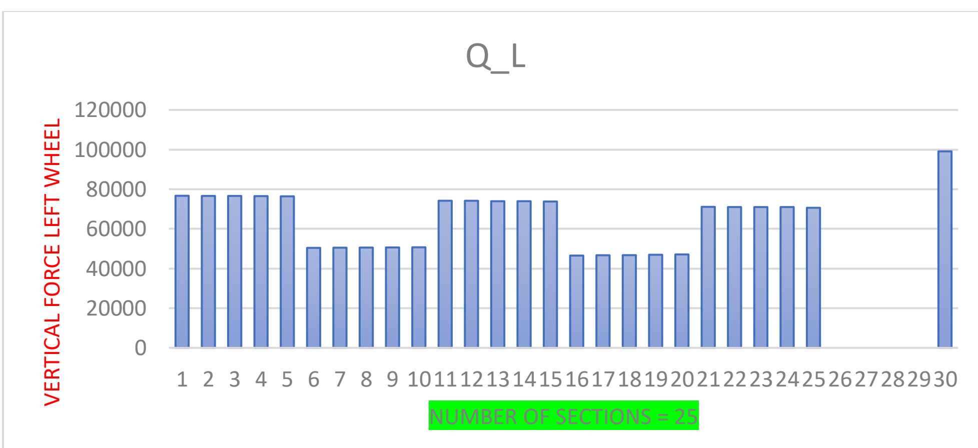
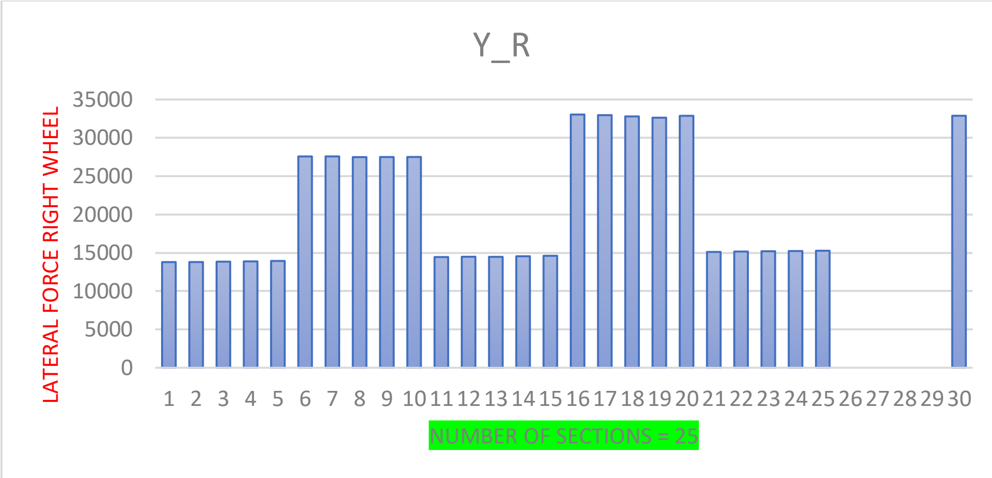


Fig.5.43 Vertical force Q (Right & Left wheel)



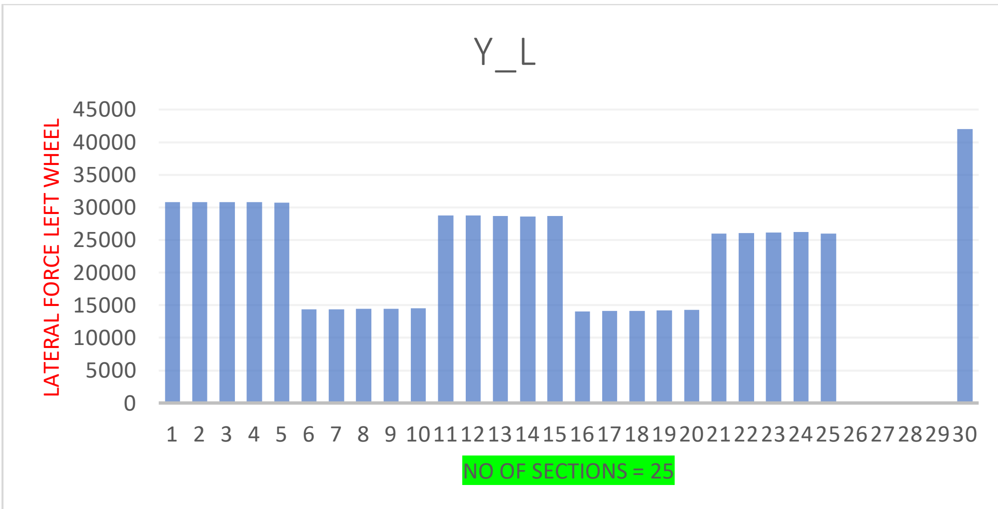


Fig.5.44 Lateral force (left & Right wheel)

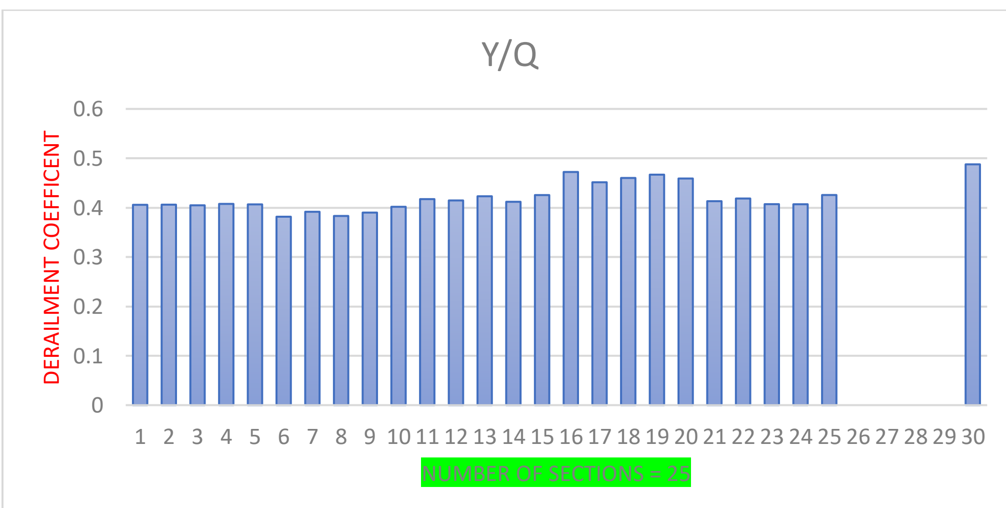


Fig.5.45 Derailment coefficient (Running safety)

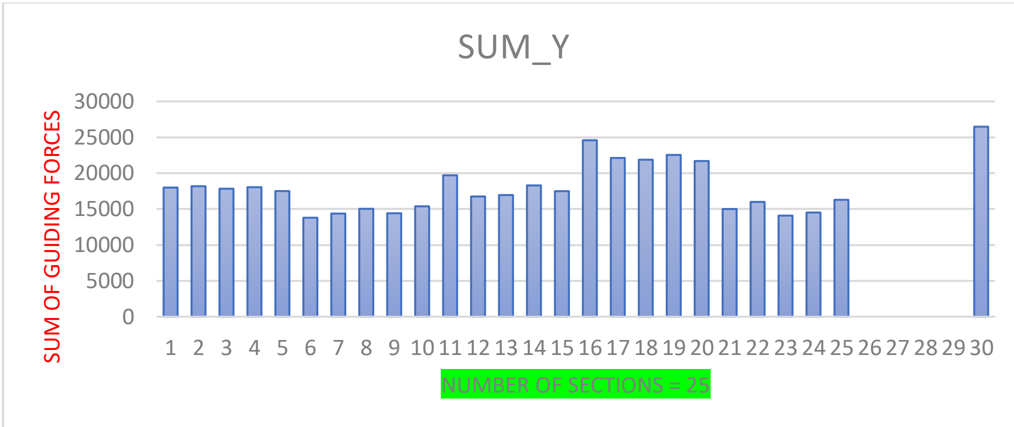
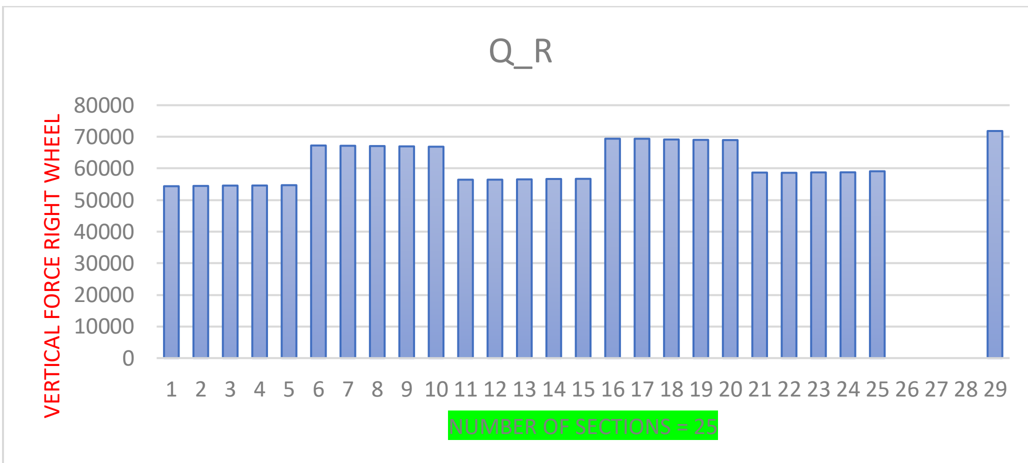


Fig.5.46 Sum of guiding forces (Running safety)

BOGIE FRONT WHEELSET 2 :-



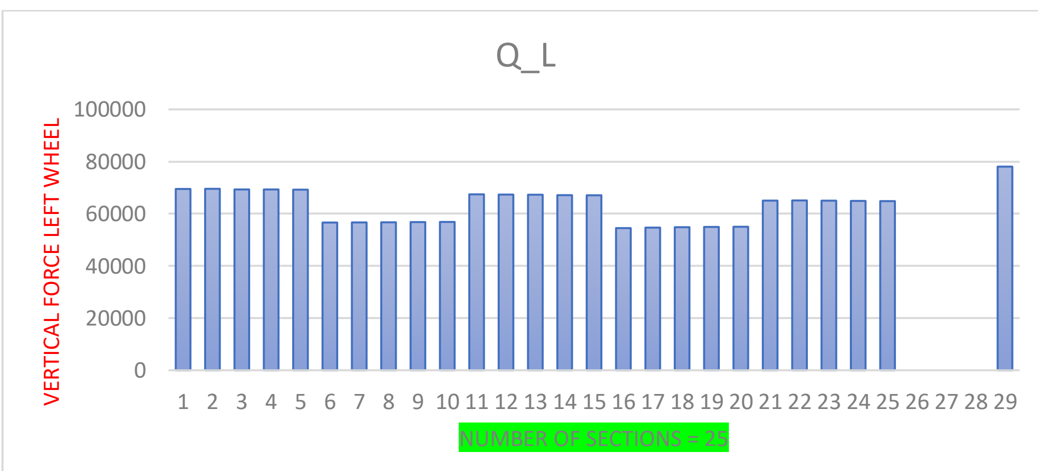
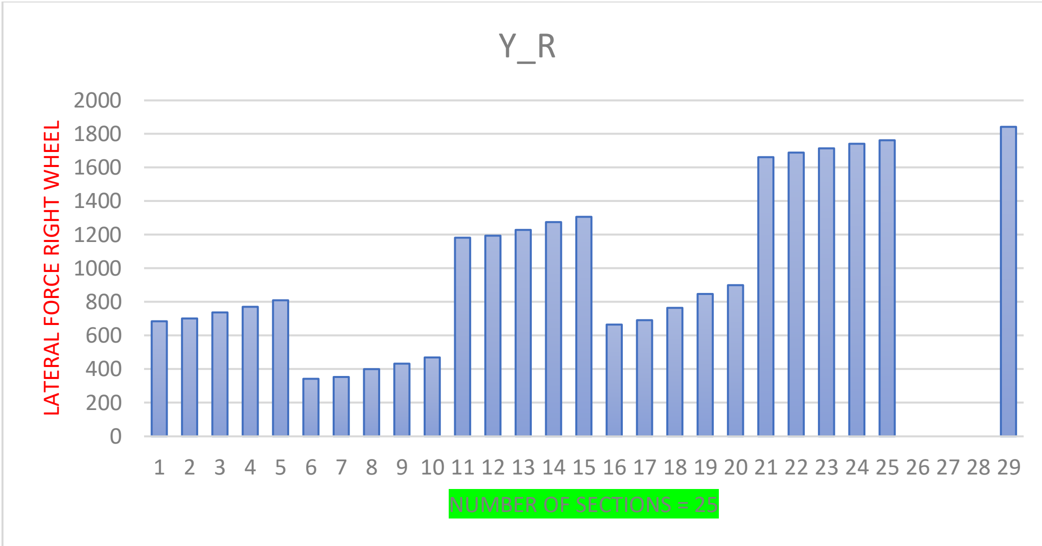


Fig.5.47 Vertical forces (Right & left wheel)



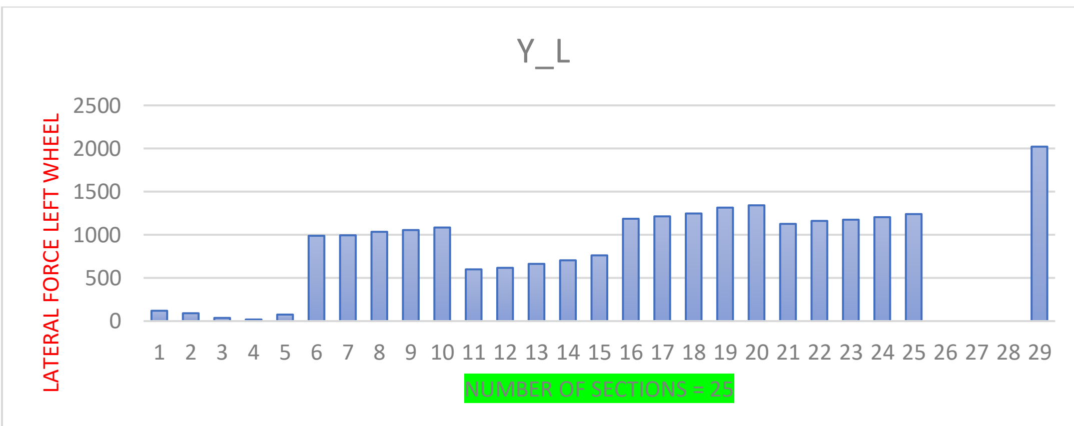


Fig.5.48 Lateral forces (Right & left wheel)

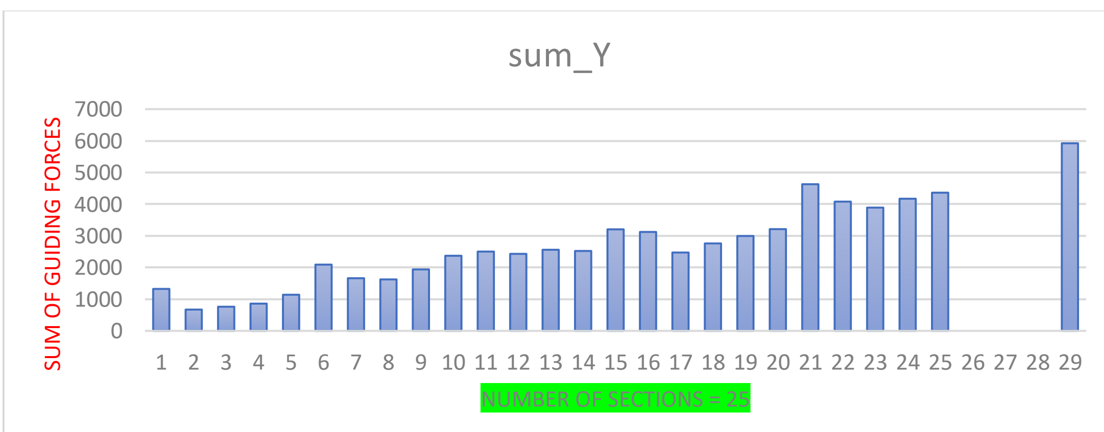
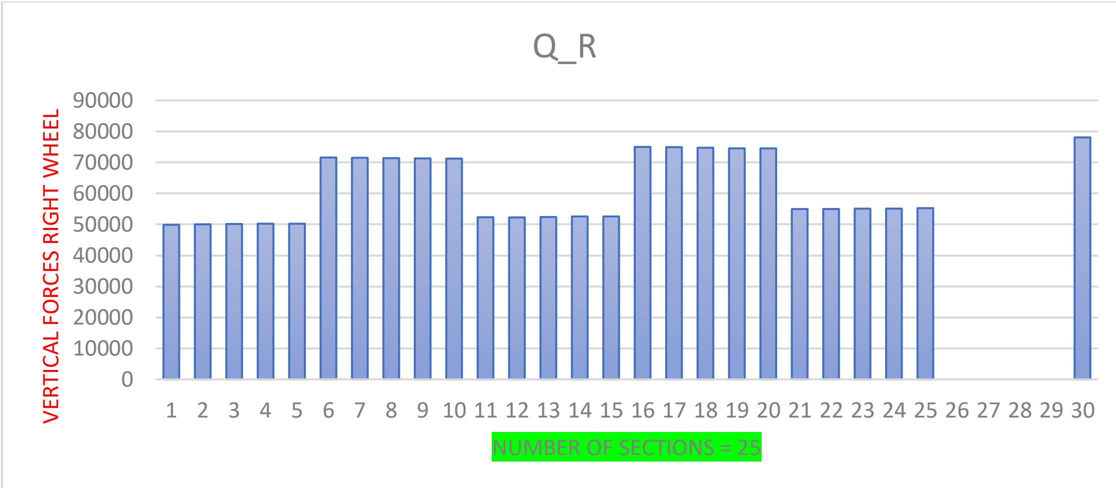


Fig.5.49 Sum of lateral forces (Running safety)

BOGIE REAR WHEELSET 1 :-



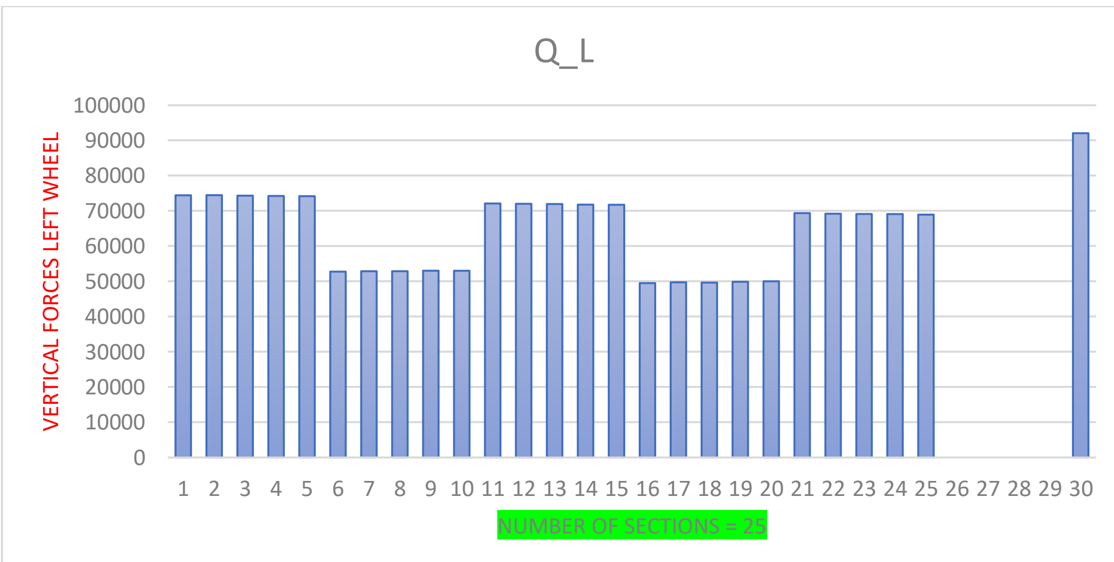
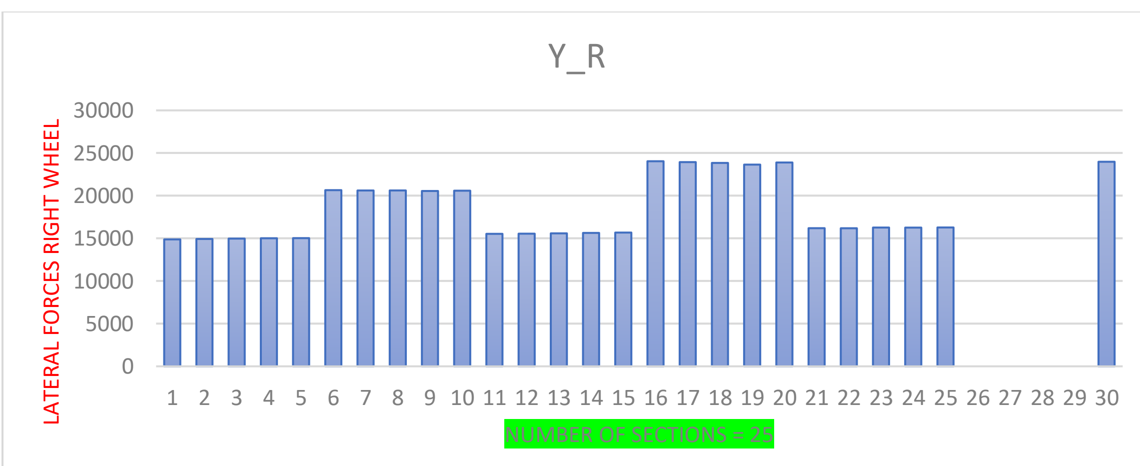


Fig.5.50 Vertical forces Q (Right & left wheel)



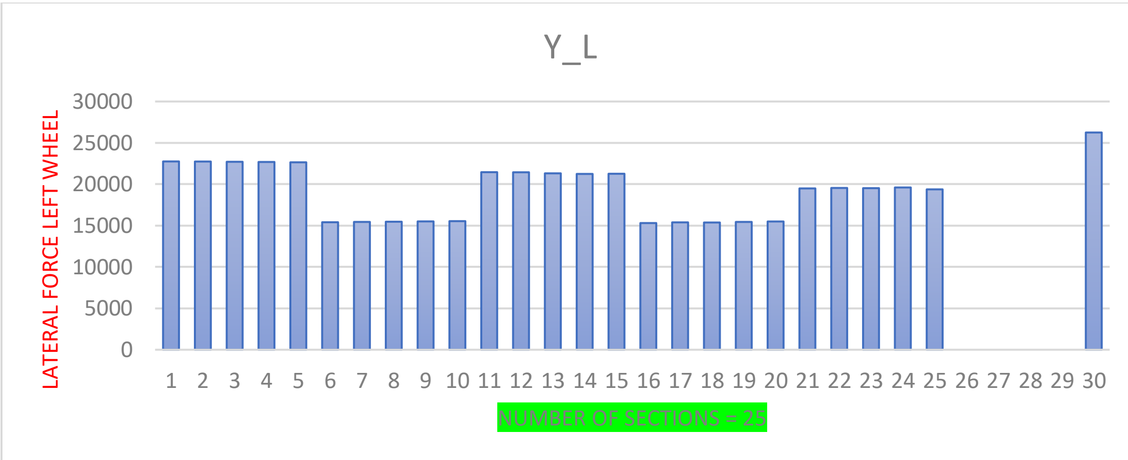


Fig.5.51 Lateral force (Right & left wheel)

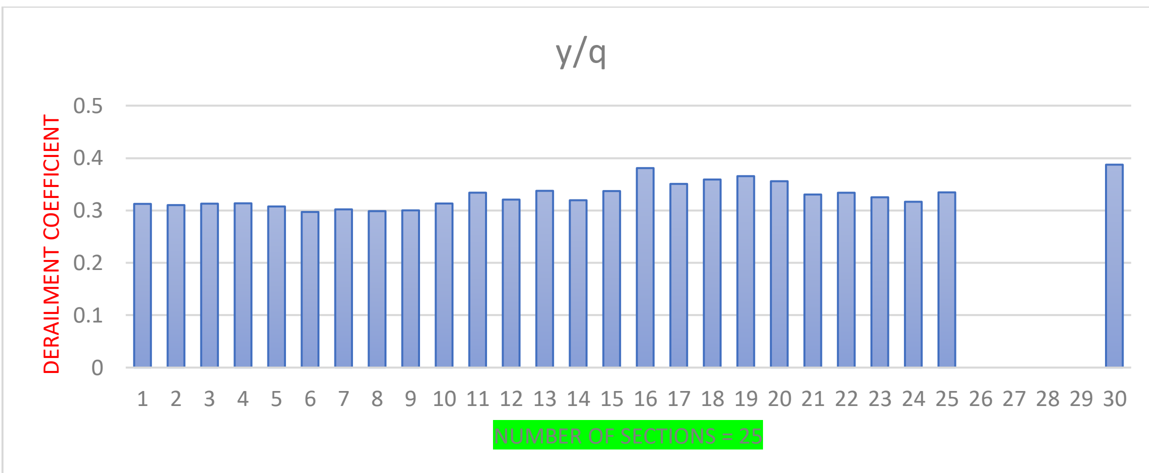


Fig.5.52 Derailment coefficient (Running safety)

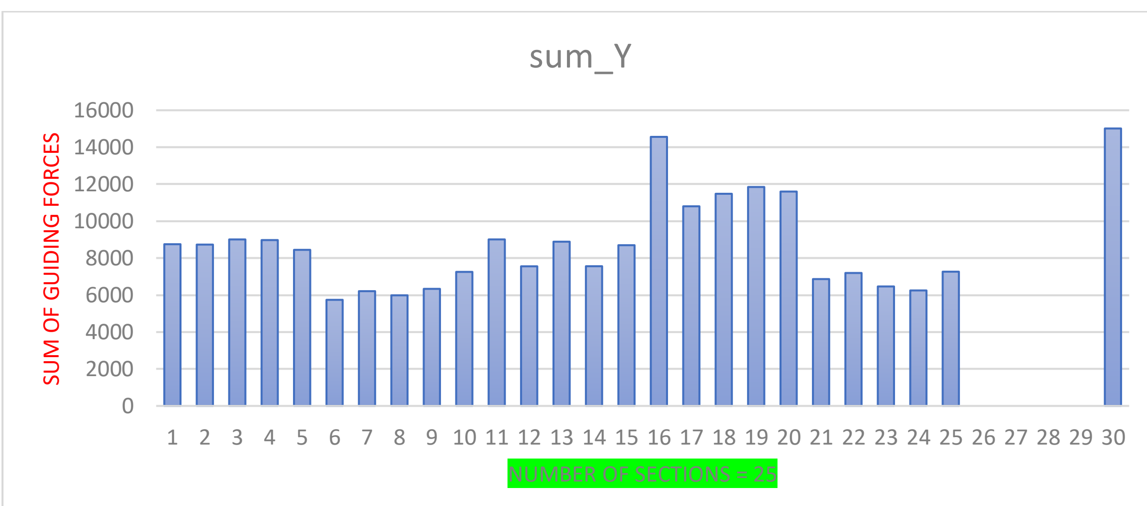
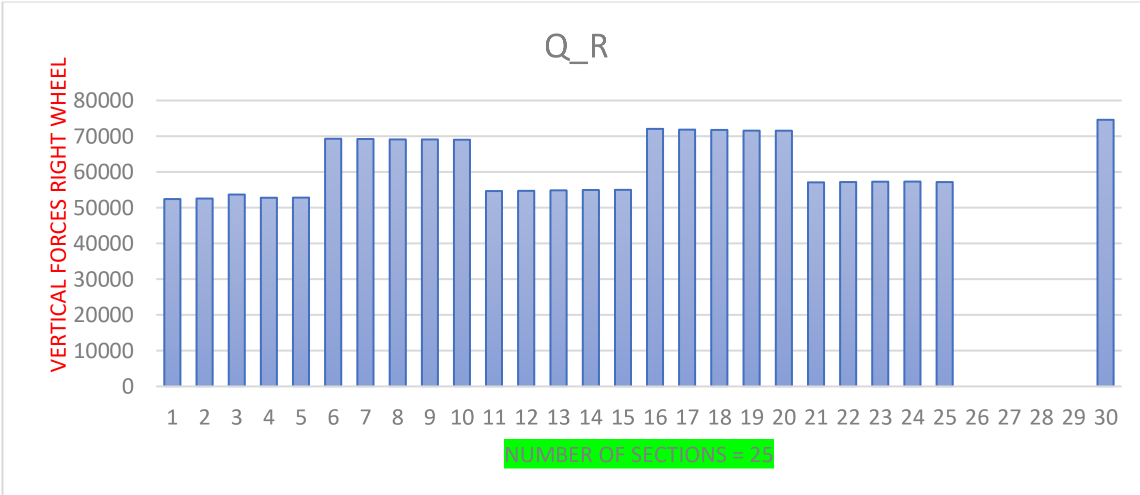


Fig.5.53 Sum of lateral forces

BOGIE REAR WHEELSET 2 :-



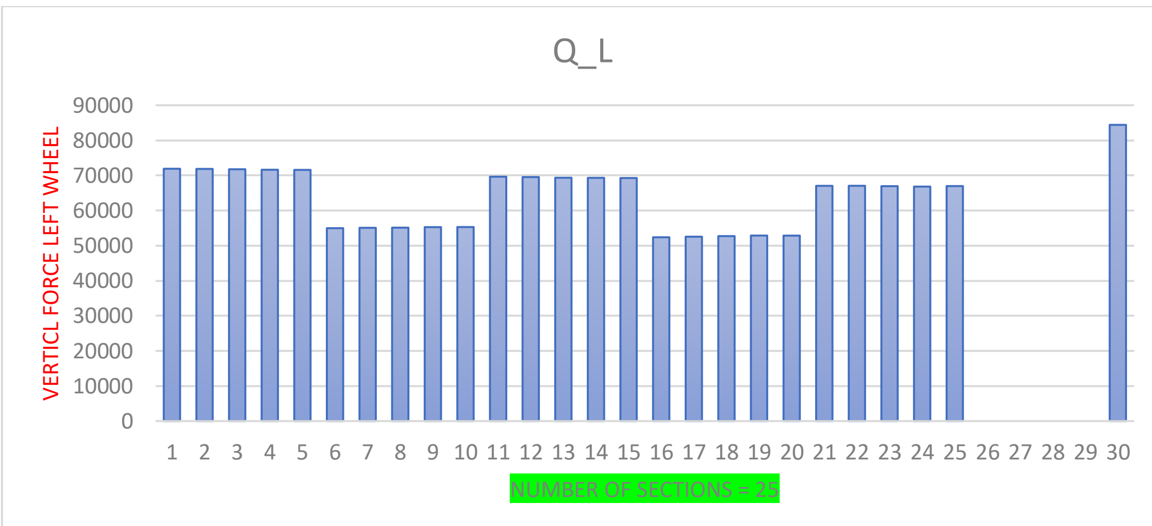
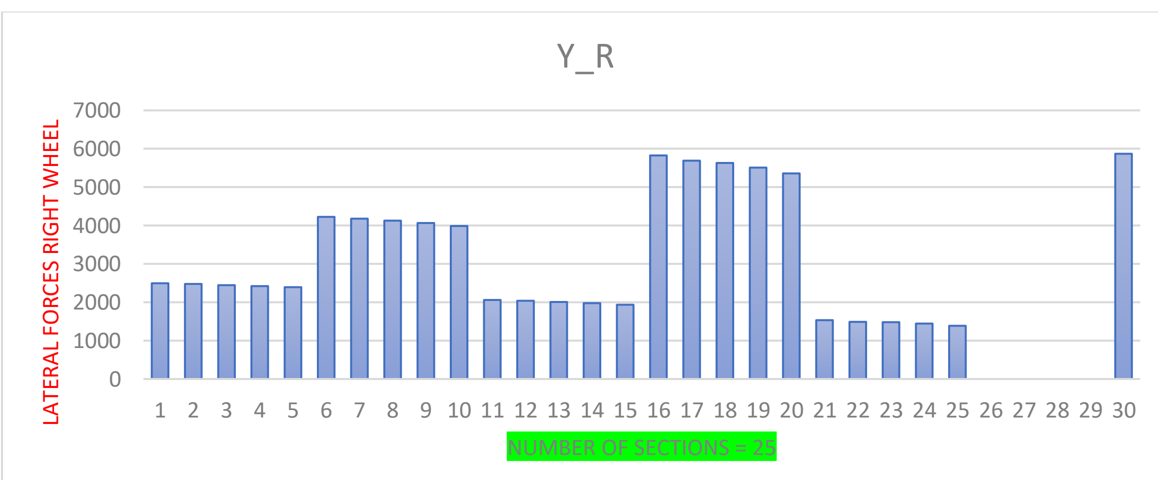
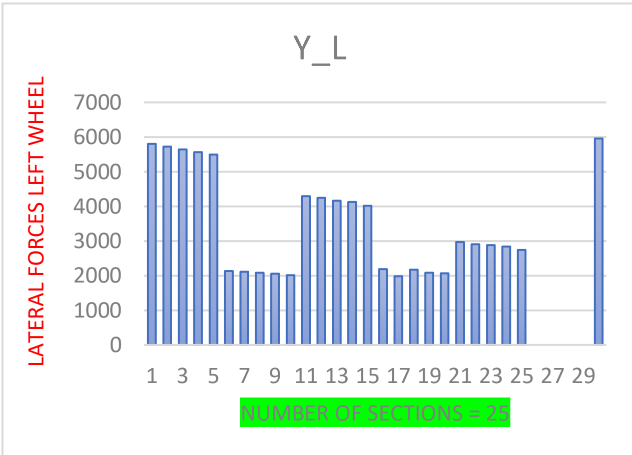


Fig.5.54 Vertical forces Q (Right & left wheel)





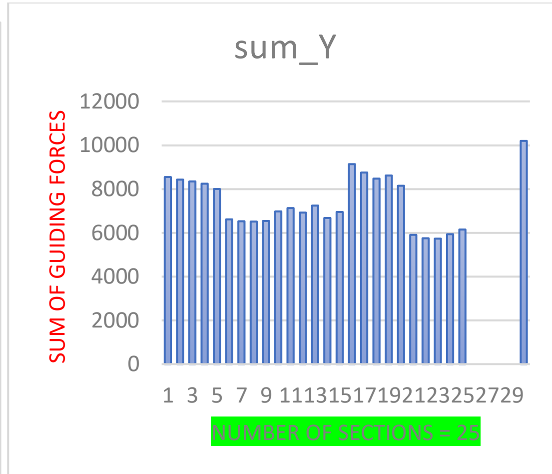


Fig.5.55 Lateral force Y (Right & left wheel) Fig.5.56 Sum of lateral forces

CAR-BODY ACCELERATIONS :-

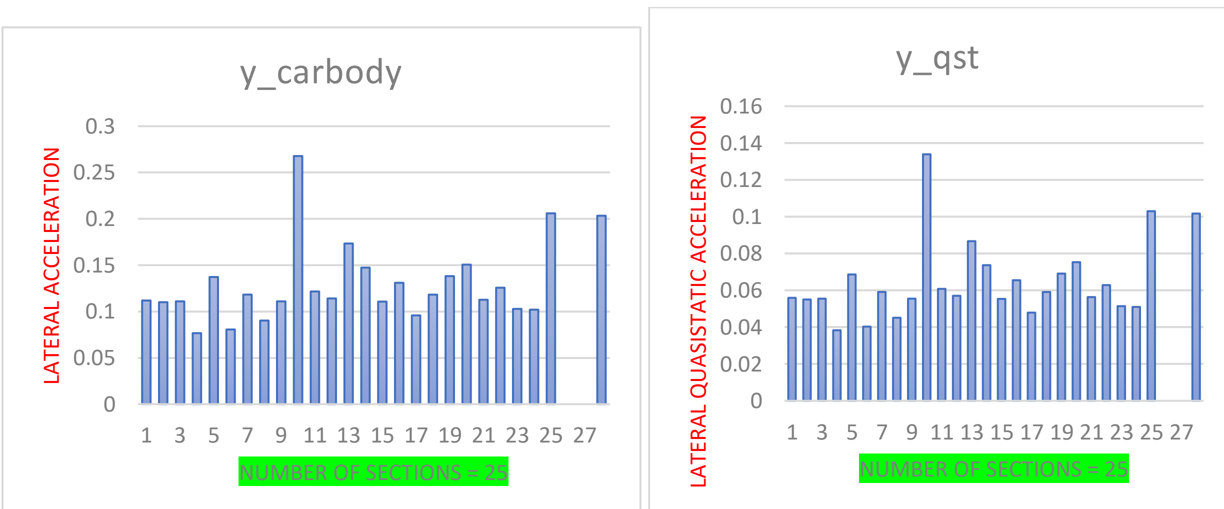


Fig.5.57 Lateral acceleration

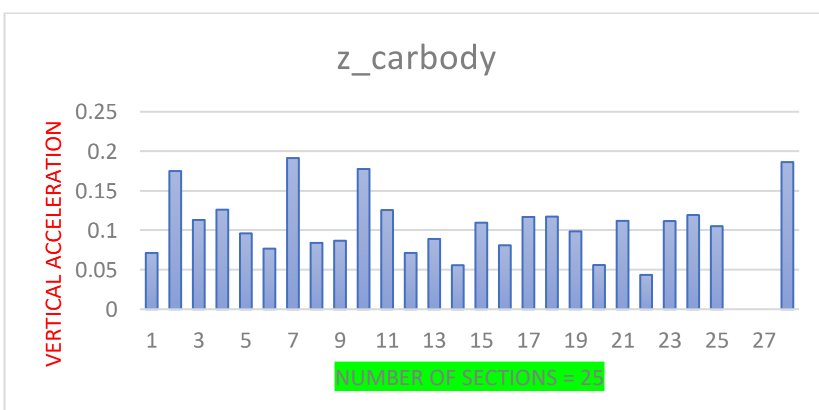


Fig.5.58 Vertical acceleration

Chapter 6

Discussion & Conclusions :-

The conclusion that has to be drawn from the current work is that simulation model is verified and all the results (Running safety, track loading, ride characteristics) obtained from the model are analyzed with limit conditions of EN 14363 standard and it clearly showed us the results of all parameter tested falls with-in the limit condition values.

ASSESSMENT QUANITIES	LIMIT VALUES EN/INDIAN	TEST ZONE 1	TEST ZONE 2	TEST ZONE 3	TEST ZONE 4
RUNNING SAFETY 1. SUM OF LATERAL FORCES [KN]	65.56 /	4.077 5.178 4.077 5.178	16.008 24.944 14.642 26.701	20.366 8.239 13.132 15.348	26.475 5.922 15.01 10.19
2. DERAILMENT COEFFICIENT	0.8 / 1.0	-	0.34 0.32	0.40 0.35	0.49 0.38
TRACK LOADING 1. QUASI-STATIC GUIDING FORCE [KN]	60 / NA	-	21.77 / 8.86 8.54 / 9.69 7.65 / 9.20 9.25 / 10.50	22.36 / 23.73 3.76 / 4.56 18.19 / 19.19 7.35 / 8.85	32.87 / 42.04 1.84 / 2.02 23.97 / 26.25 5.86 / 5.95
2. QUASI-STATIC WHEEL FORCE [KN]	145 / NA	-	65.45 / 81.25 63.25 / 86.25 70.65 / 81.36 69.65 / 82.36	70.25 / 86.26 75.36 / 76.59 65.36 / 80.32 68.95 / 81.63	81.07 / 65.68 65.56 / 56.98 83.35 / 71.65 79.84 / 75.06
3. MAXIMUM WHEEL FORCE [KN]	173.38 / NA	-	75.88 / 90.97 77.04 / 93.47 76.07 / 90.32 78.03 /	78.85 / 94.05 84.26 / 85.26 77.08 / 89.70 76.07 /	103.1/ 83.45 71.84 /78.05 78.08 / 92.05 74.59/

			94.50	88.28	84.40
RIDE CHARACTERISTICS 1. ACCELERATION IN CAR-BODY [m/s²]	2.5 / 2.75 & 3.0	0.45 / 0.48	0.67 / 0.63	0.6 / 0.46	0.20 / 0.18

Table.21 Comparison on results with limit values

When looking at the simulation results that the vehicle with its current configuration probably would pass the authority approval test. The testing of running stability showed that the vehicle handles high equivalent conicity without becoming unstable, and when instability occurred the wheel rail forces were still under their respective limit values. If running stability would become a problem the easiest solution would be to increase the longitudinal stiffness in the primary suspension. This would however lead to higher wheel-rail forces in curves since it would be harder for the wheels to follow in curves. And even though the wheel rail forces probably wouldn't exceed the limit values, so they would lead to high wear on wheels.

The results on ride comfort showed us the minimal possible value attained in the simulations, one of the possible reasons is the wheel – rail contact and the other where if some of the properties of vehicle suspension were changed which can results in improving the vehicle ride comfort performance. High damper constant lead to high damper forces even at low piston velocities. Given the vehicle's weight this would lead to it being stiff in almost all damper directions. Softening the damper by having a smaller constant could lead to better results in lower frequency range in which the dynamic behavior is studied. Other changes that were studied but not presented were softer lateral primary stiffness to improve the response for lateral acceleration in the car-body.

Bibliography

[1] *EN 14363,* Railway applications - *Testing for the acceptance of running characteristics of railway vehicles - Testing of running behavior and stationary tests,* Brussels: European committee for standardization, 2005.

[2] ERA/TD/2012-17/INT - Running dynamics – Applications of EN14363:2005

[3] UIC-518 - Testing and approval of railway vehicles from the point of view of dynamic behavior – Safety , Track fatigue , Running behavior

[4] K. Knothe and S. Stichel, Rail Vehicle Dynamics, Springer International Publishing AG 2017 DOI 10.1007/978-3-319-45376-7_10..

[5] Wickens, A. H., Fundamentals of Rail Vehicle Dynamics—Guidance and Stability, Swets & Zeitlinger, Lisse, 2003.

[6] Maksym Spiryagin, Colin Cole, Yan Quan Sun, Tim McSweeney, Design & Simulation of Rail vehicles.

[7] Simpack9.10.2 Documentation. 2016,Dassault Systems Simulia Corp.

[8] Prof. Binbin Liu, Lectures on Modelling and simulation, Rail Vehicle Dynamics & Train track interaction, Politecnico Di Milano

[9] Rakesh Chandmal Sharma, modelling and simulation of railway vehicle system, International Journal on Mechanical Engineering and Robotics research, ISSN 2278-0149, Vol No – 1, 2014.

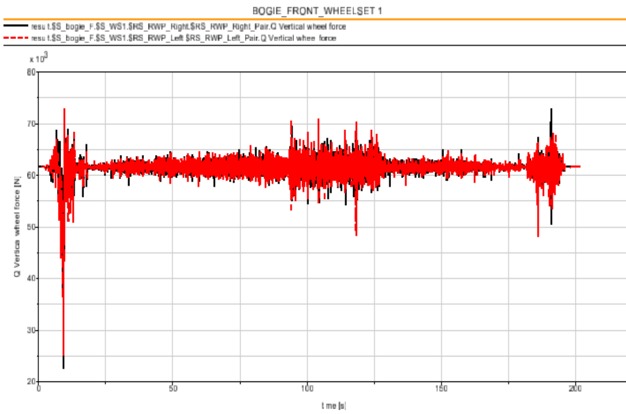
[10] A technical guide on Derailments, Centre for Advanced Maintenance Technology, Ministry of Railways, RDSO, Indian Railways.

[11] Maintenance Manual for LHB coaches, Centre for Advanced maintenance technology, Ministry of Railways, RDSO, Indian Railways.

APPENDIX : A

TEST ZONE 1 RESULTS :

Bogie Front Wheelset 1 & 2 Force Results :-



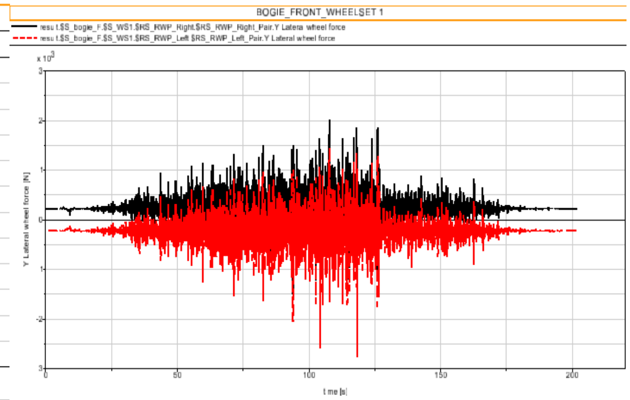
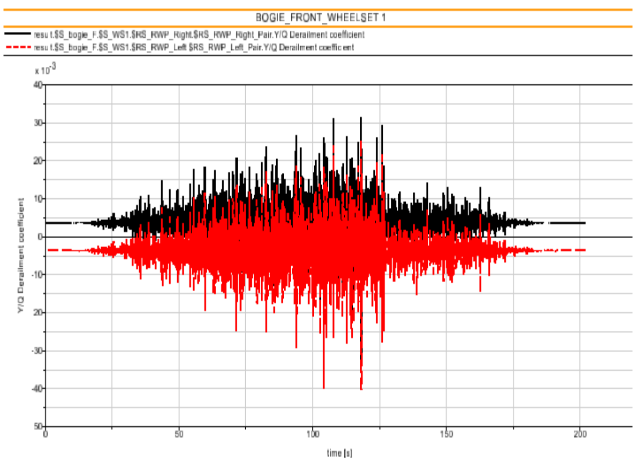


Fig.1 Vertical force Q & Lateral force Y(left and right wheel)



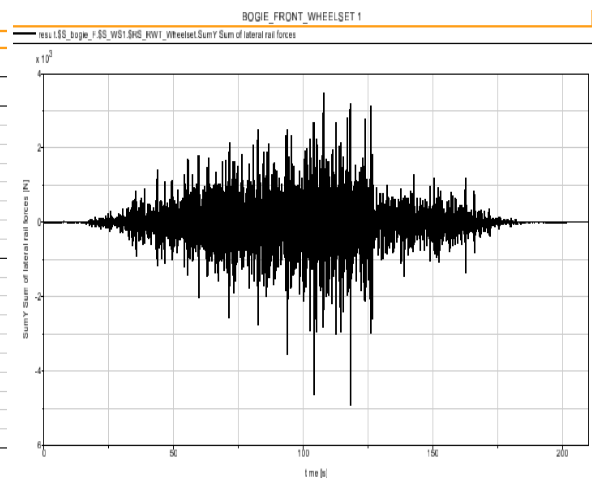
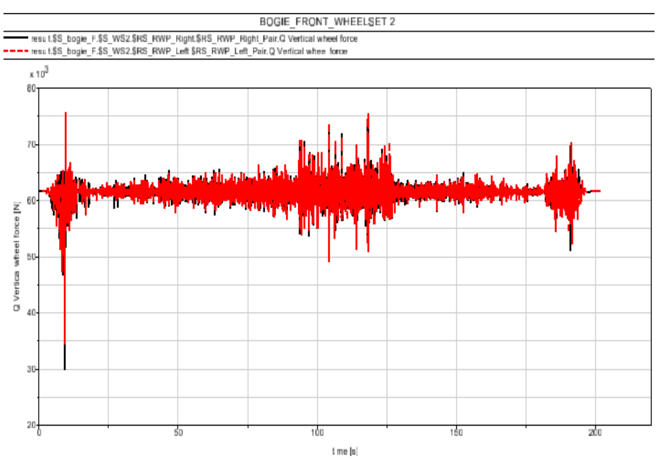


Fig.2 Quotient of lateral and vertical forces (Y/Q) **Fig.3 Sum of lateral forces wheelset 1**



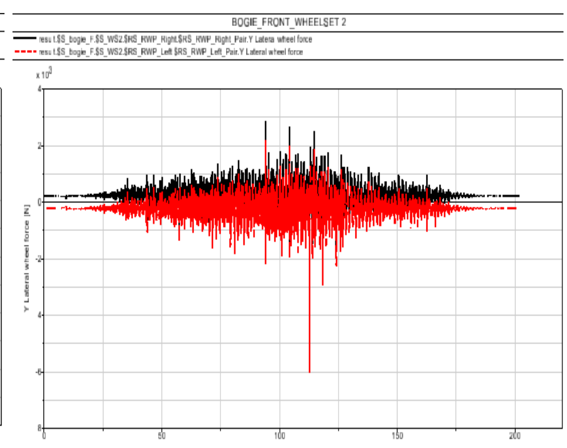
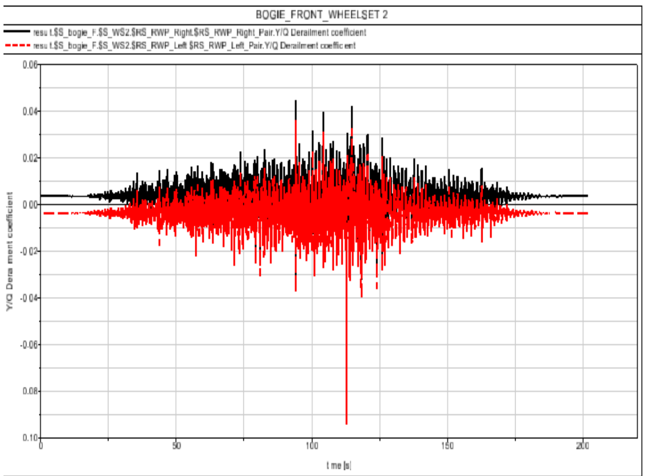


Fig.4 Vertical force Q & Lateral force Y wheelset 2



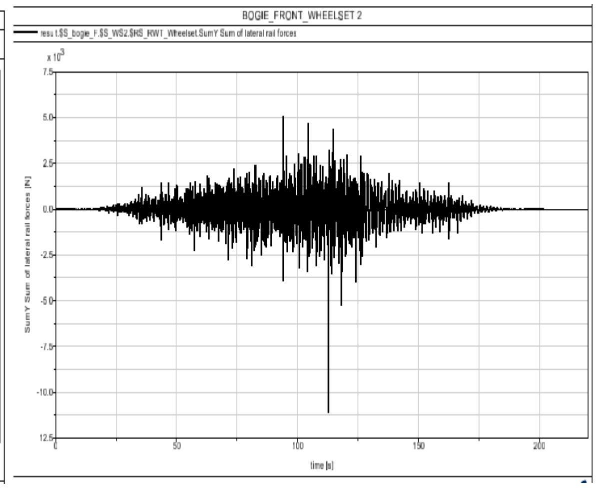
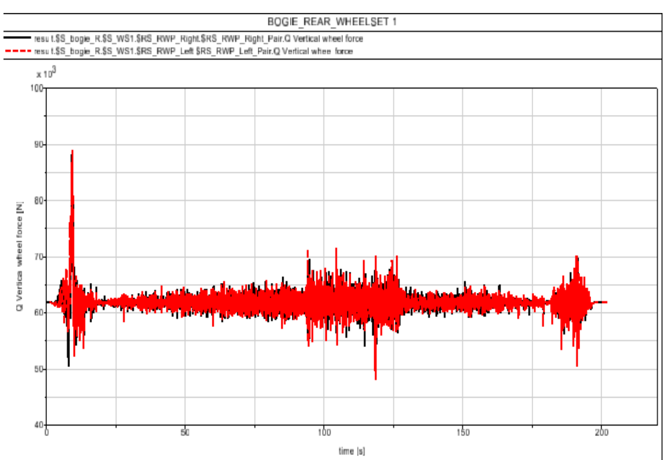


Fig.5 Quotient of lateral and vertical forces (Y/Q) Fig.6 Sum of lateral forces wheelset 2

Bogie Rear Wheelset 1 & 2 Force Results :-



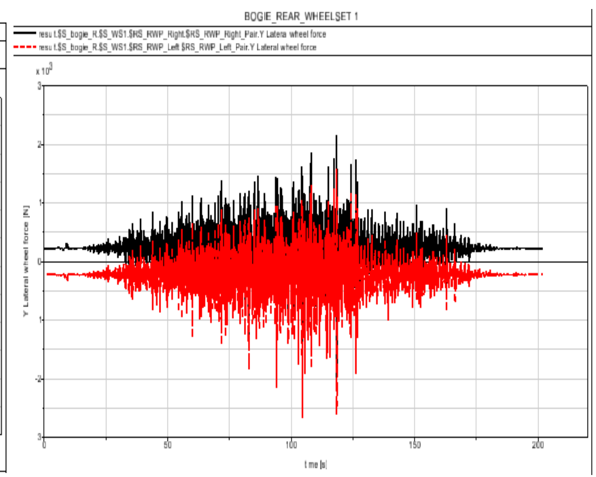
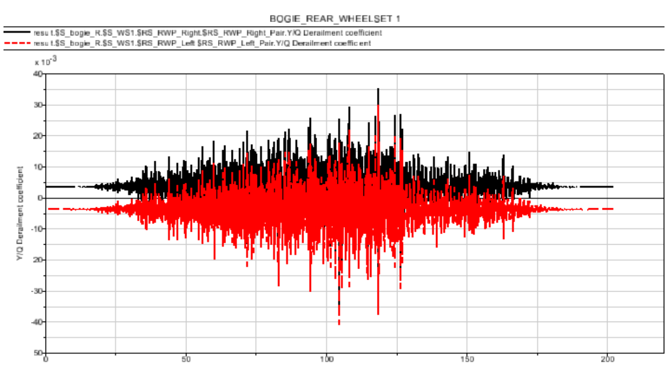


Fig.7 Vertical force wheelset 1

Fig.8 Lateral force wheelset 2



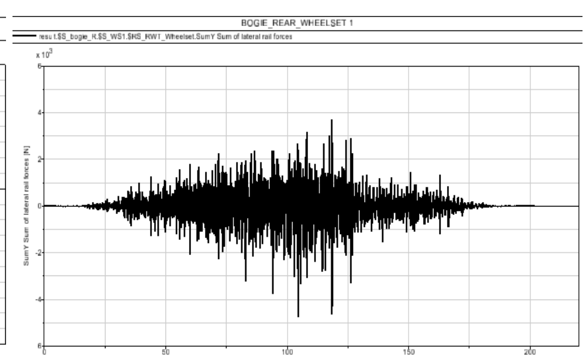
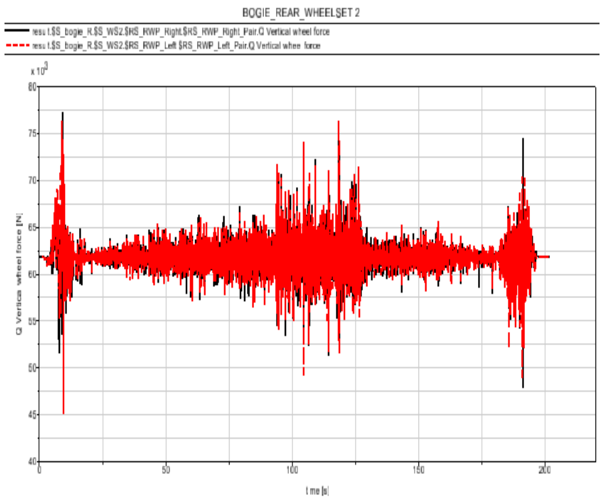


Fig.9 Quotient of lateral over vertical force (Y/Q) Fig.10 Sum of lateral force wheelset 1



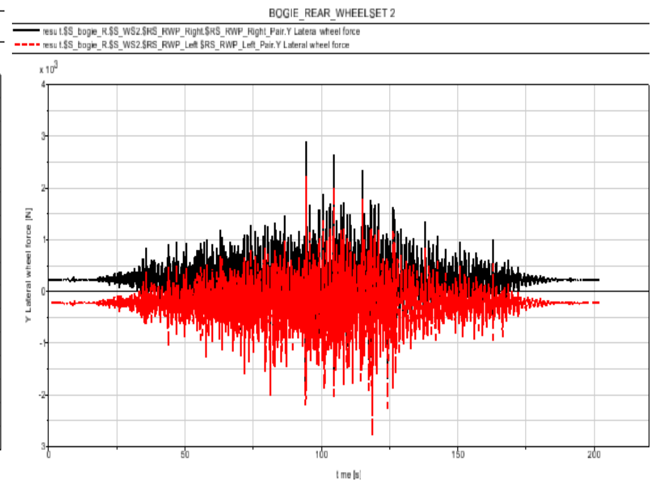
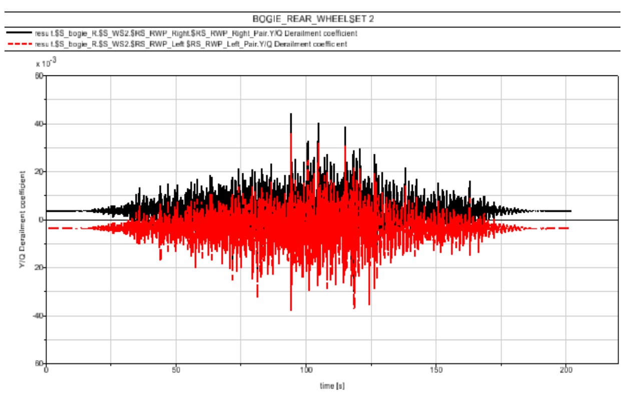


Fig.11 Vertical force wheelset 2 **Fig.12 Lateral force wheelset 2**



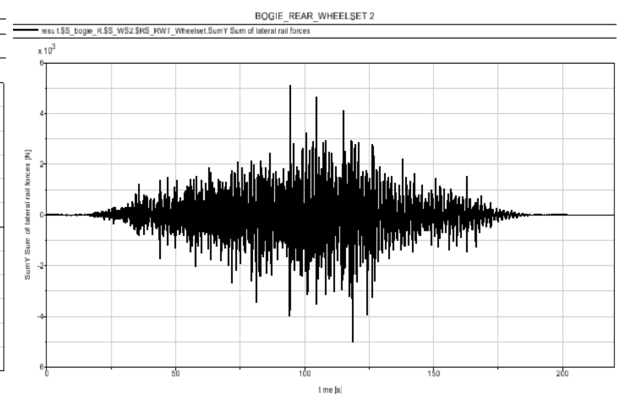
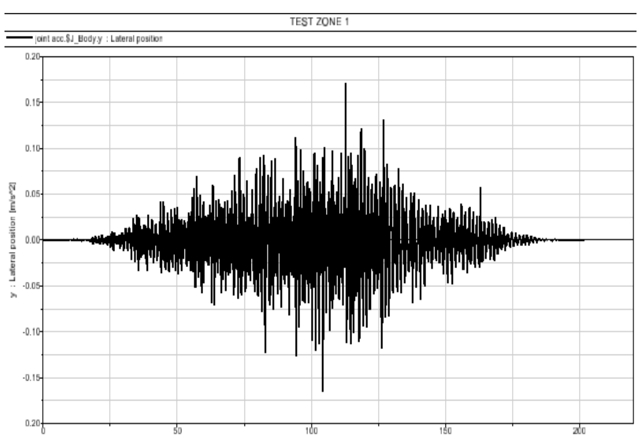


Fig.13 Quotient of lateral over vertical force **Fig.14 Sum of lateral forces**

Acceleration in Car-body :-



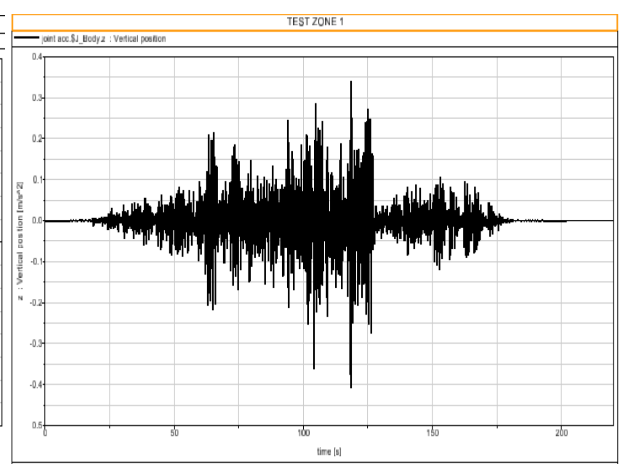


Fig.15 lateral acceleration y car-body **Fig.16 Vertical acceleration z car-body**

TEST ZONE 2 RESULTS :-

Bogie Front Wheelset 1 & 2 Force Results :-

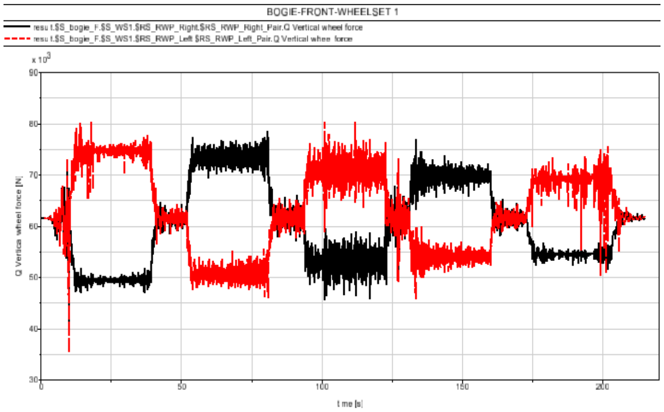


Fig.17 Vertical force Q wheelset 1

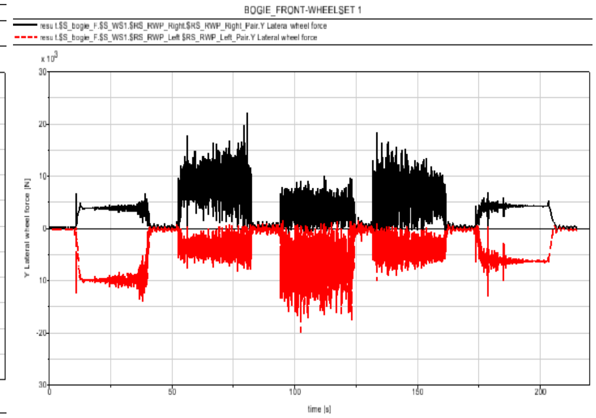


Fig.18 Lateral force Y wheelset 1

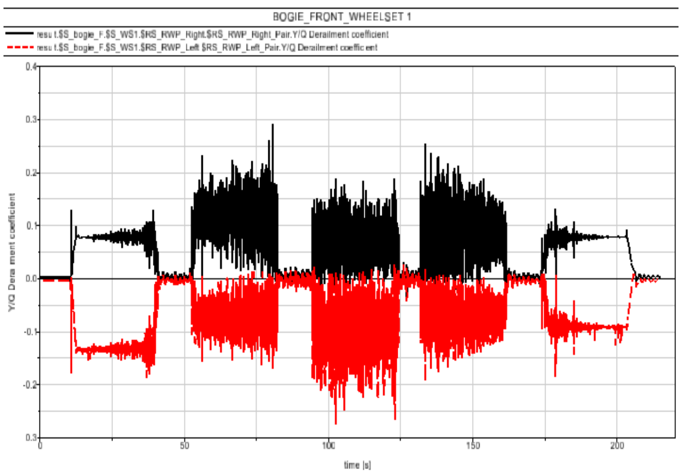


Fig.19 Quotient of lateral over vertical force (Y/Q)

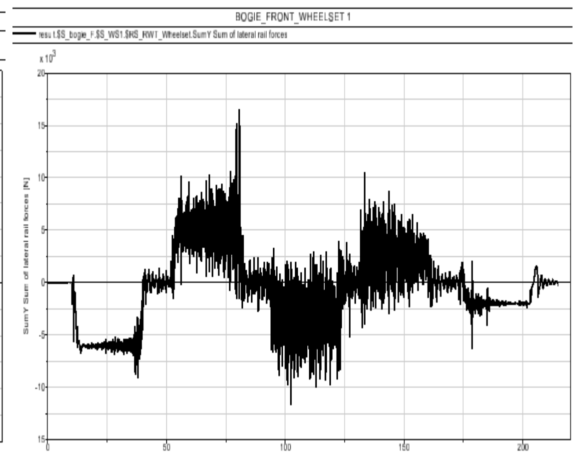


Fig.20 Sum of lateral forces wheelset 1

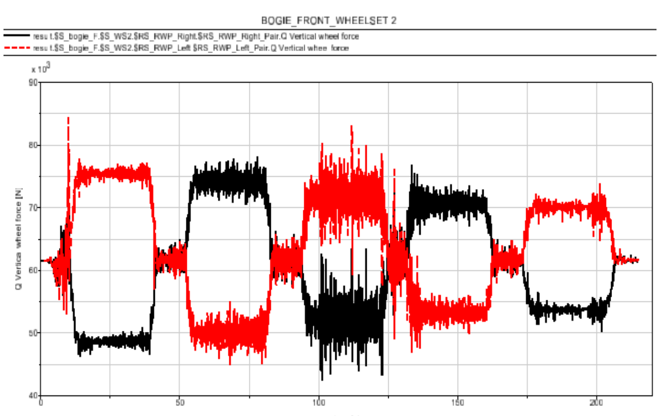


Fig.21 Vertical force Q wheelset 2

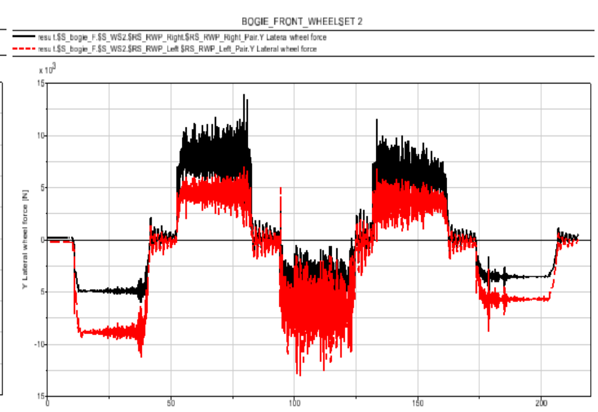
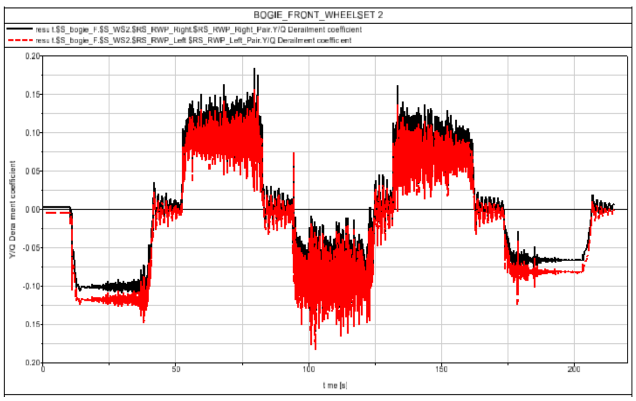


Fig.22 Lateral force Y wheelset 2



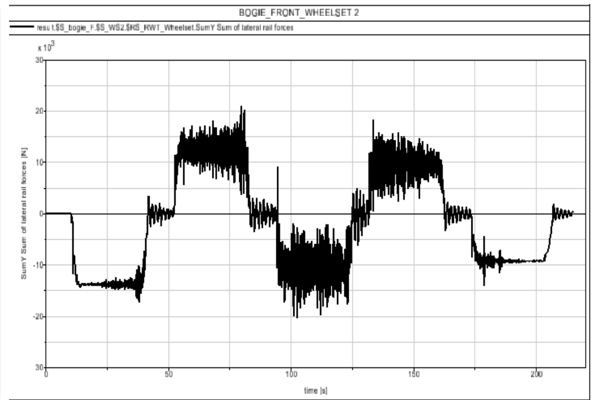
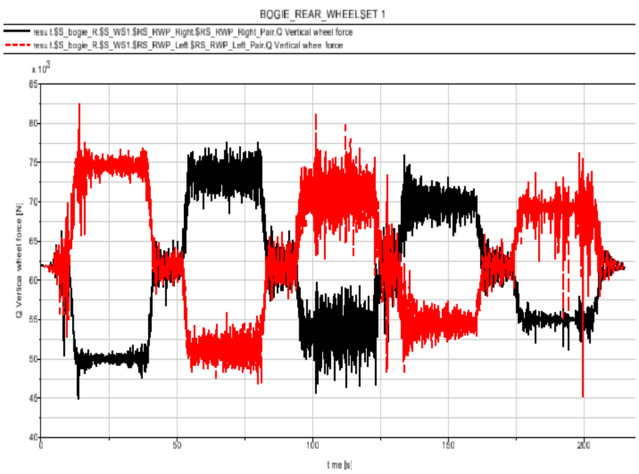


Fig.23 Quotient of lateral over vertical (Y/Q) **Fig.24 Sum of lateral force wheelset 2**

Bogie Rear Wheelset 1 & 2 Force Results :-



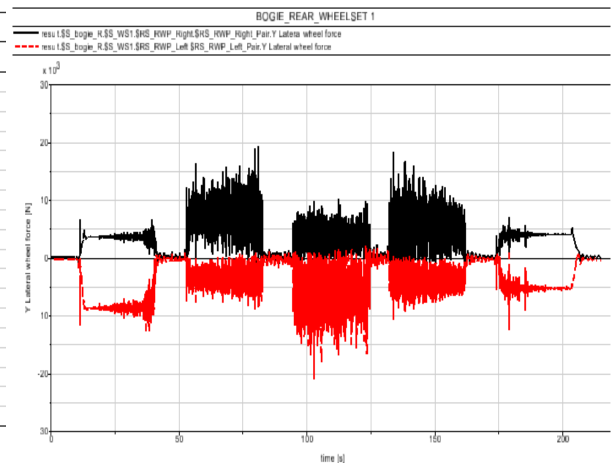
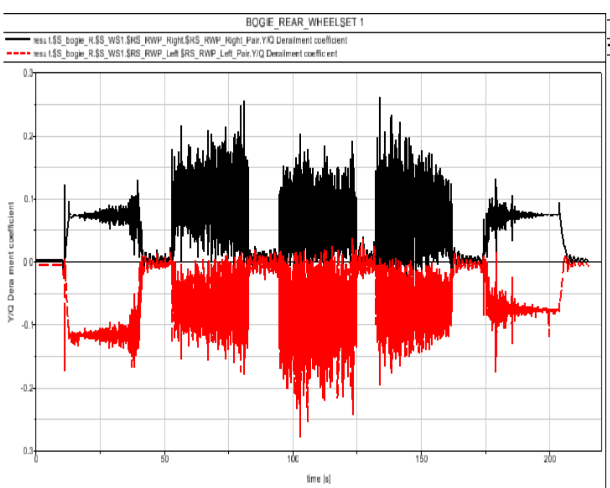


Fig.25 Vertical force Q wheelset 1 **Fig.26 Lateral force Y wheelset 1**



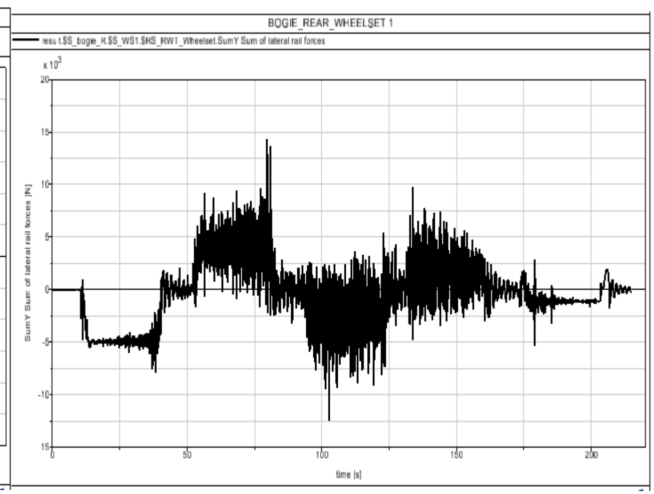
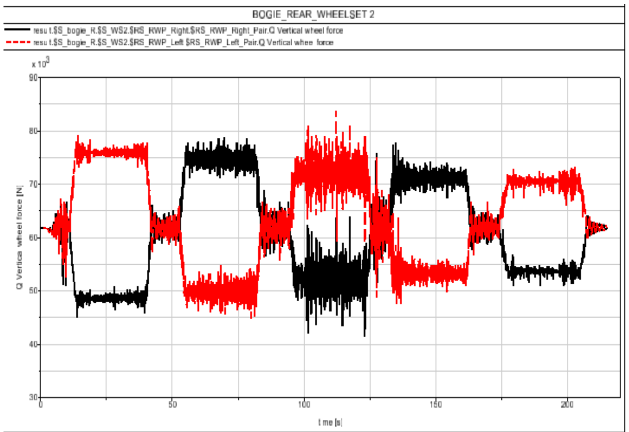


Fig.27 Quotient of lateral over vertical force (Y/Q) **Fig.28 Sum of lateral force wheelset**



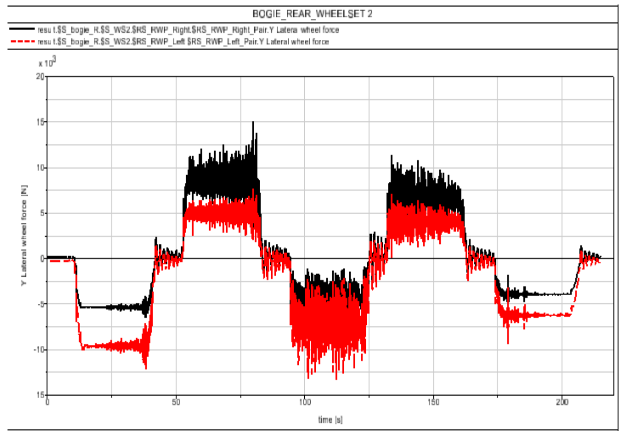
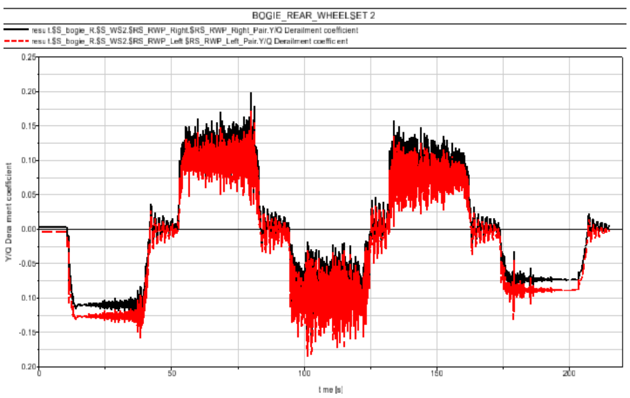


Fig.29 Vertical force Q wheelset 2 **Fig.30 Lateral force Y wheelset 2**



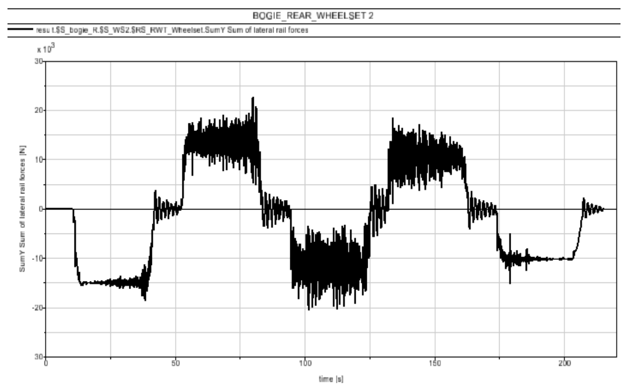
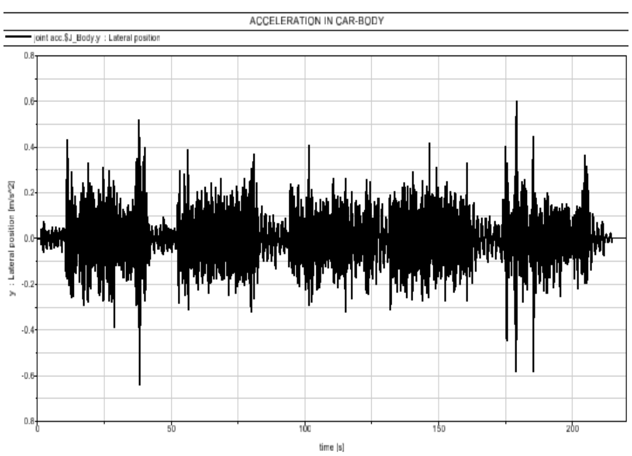


Fig.31 Quotient of lateral over vertical force (Y/Q) **Fig.32 Sum of lateral force wheelset 2**

Acceleration Results in Car-Body :-



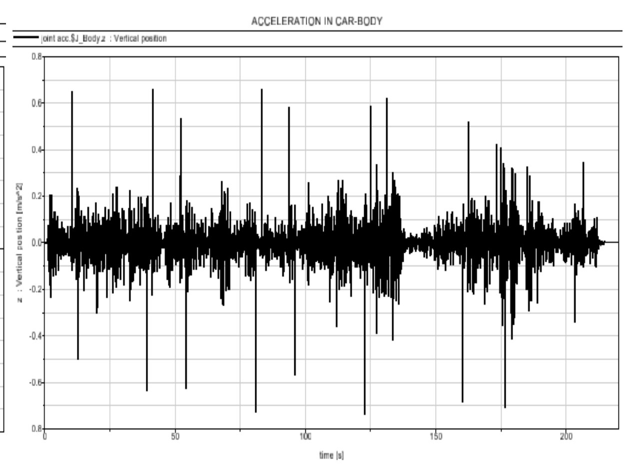


Fig.33 Lateral acceleration car-body **Fig.34 vertical acceleration car-body**

TEST ZONE 3 RESULTS :-

Bogie Front Wheelsets 1 & 2 Force Results :-

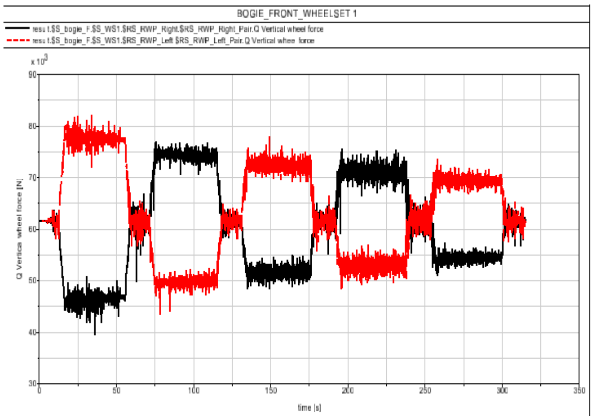


Fig.35 Vertical force Q wheelset 1

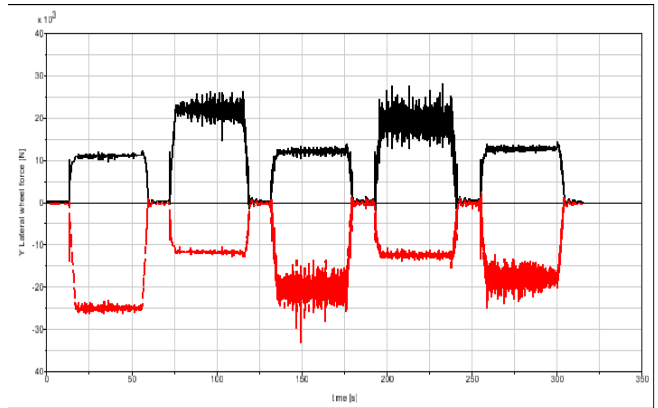


Fig.36 Lateral force Y wheelset 1

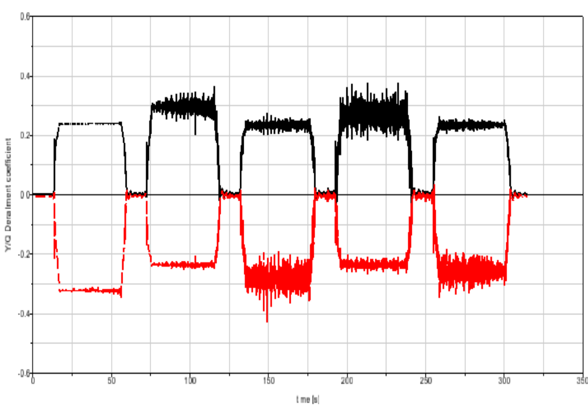


Fig.37 Quotient of lateral over vertical force (Y/Q)

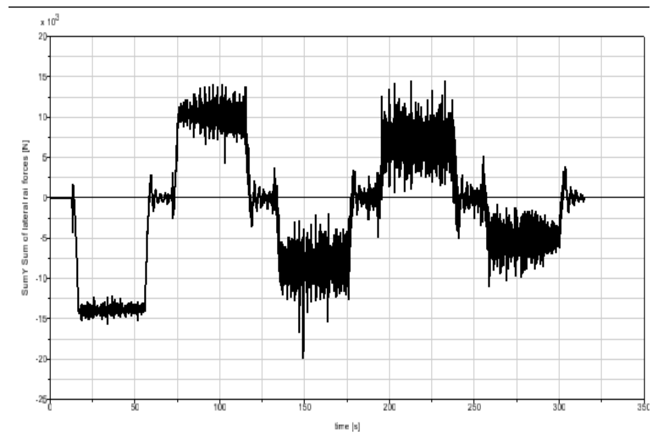


Fig.38 Sum of lateral force wheelset 1

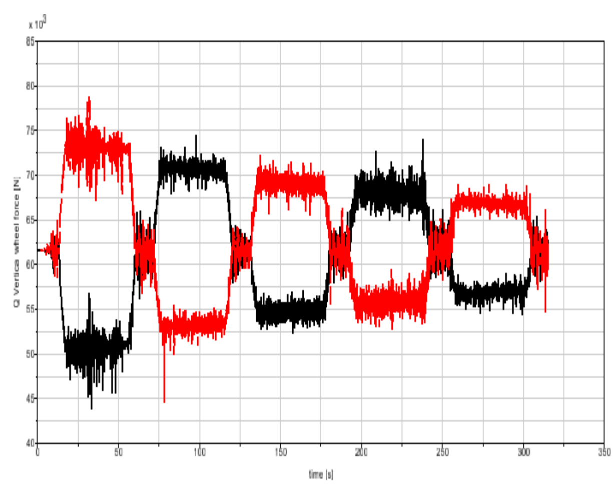


Fig.39 Vertical force Q wheelset 1

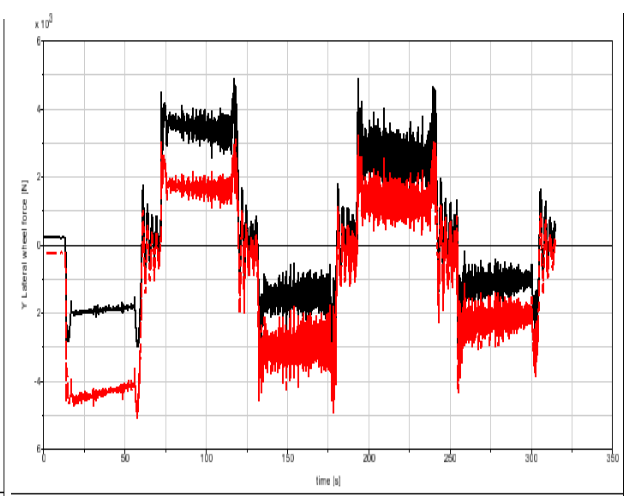
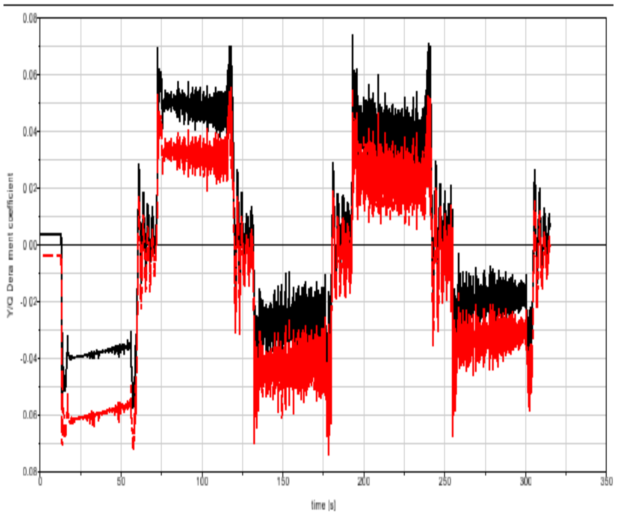


Fig.40 Lateral force Y wheelset 2



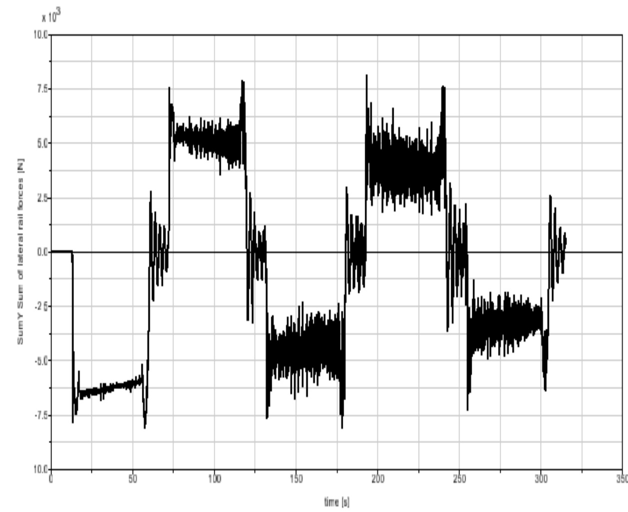
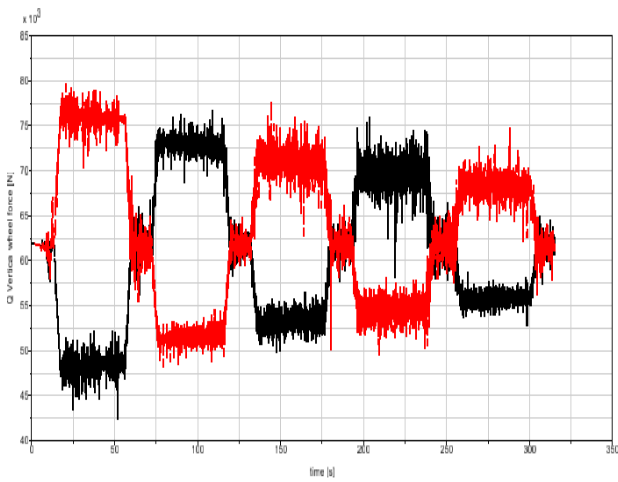


Fig.41 Quotient of lateral over vertical force (Y/Q) **Fig.42 Sum of lateral forces wheelset 2**



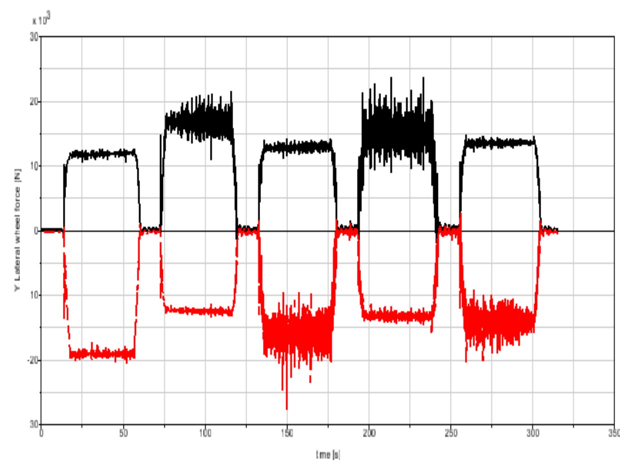
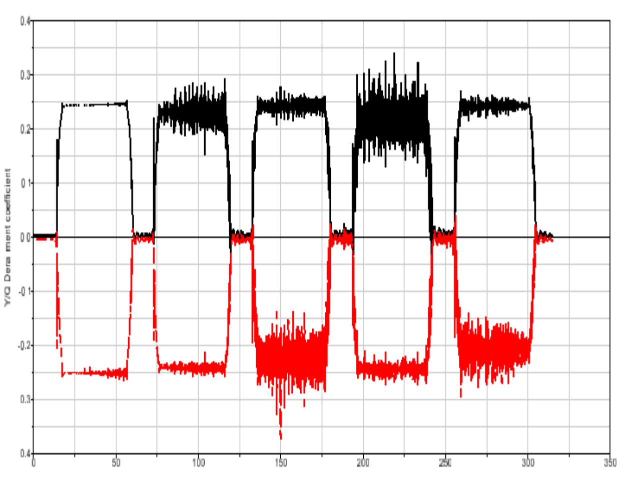


Fig.43 Vertical force Q wheelset 1 **Fig.44 lateral force Y wheelset 1**



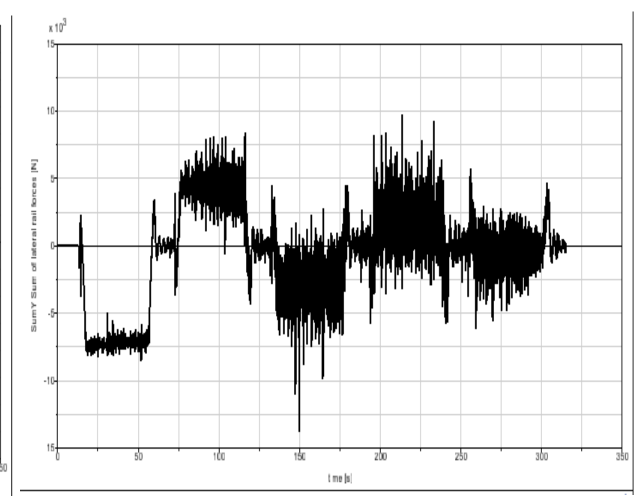
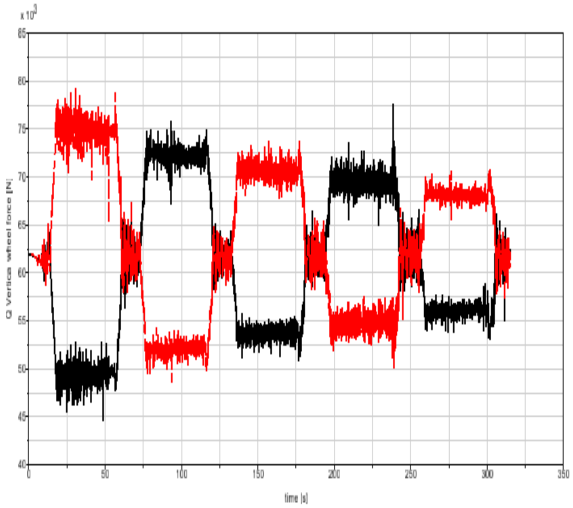


Fig.45 Quotient of lateral over vertical force (Y/Q) **Fig.46 Sum of lateral forces wheelset 1**



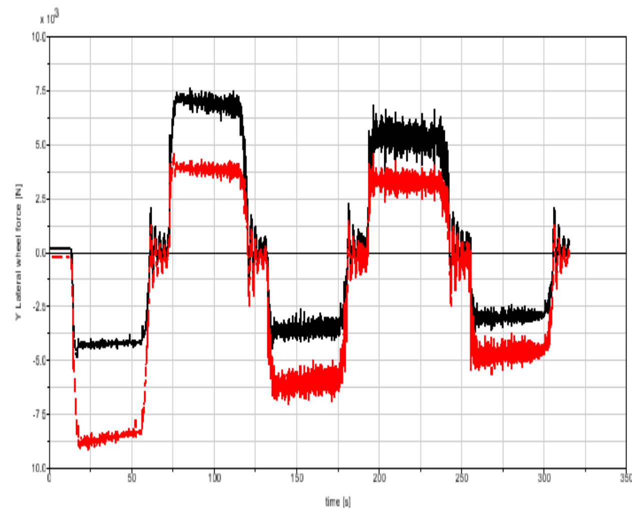
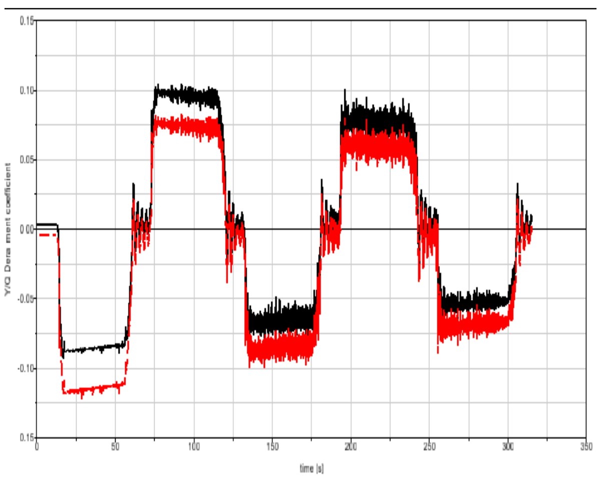


Fig.47 Vertical force Q wheelset 2 **Fig.48 lateral force Y wheelset 2**



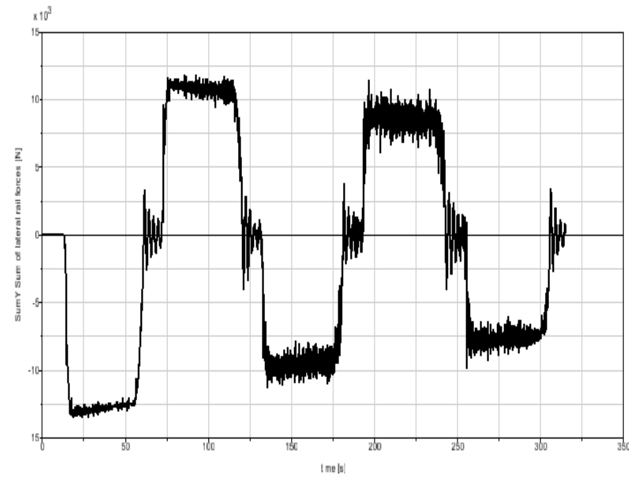


Fig.49 Quotient of lateral over vertical force (Y/Q **Fig.50 Sum of lateral forces wheelset 2**

Accelerations in Car Body Test Zone 3 :-

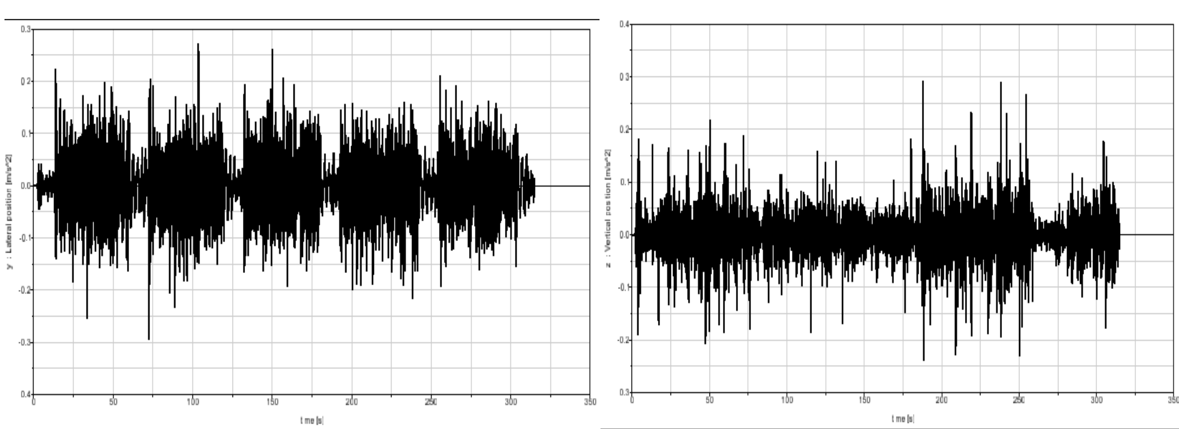


Fig.51 Lateral and vertical acceleration in car-body

TEST ZONE 4 RESULTS :-

Bogie Front Wheelset 1 & 2 Force Results

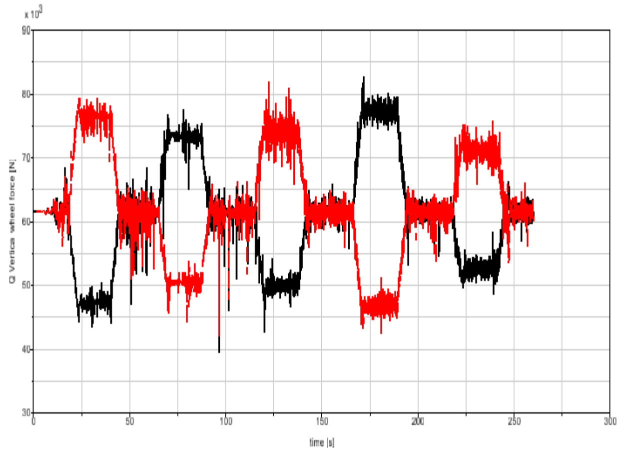


Fig.52 Vertical force Q wheelset 1

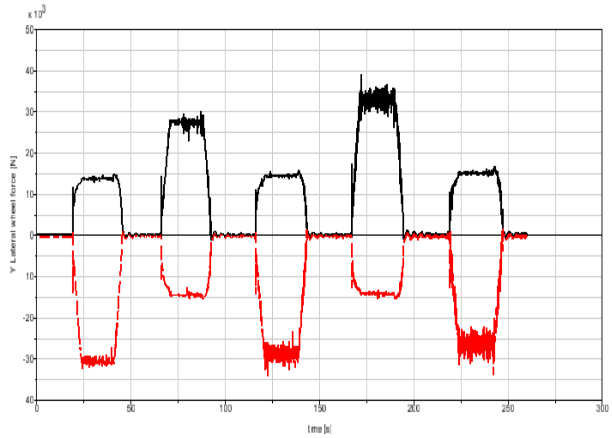


Fig.53 Lateral force Y wheelset 1

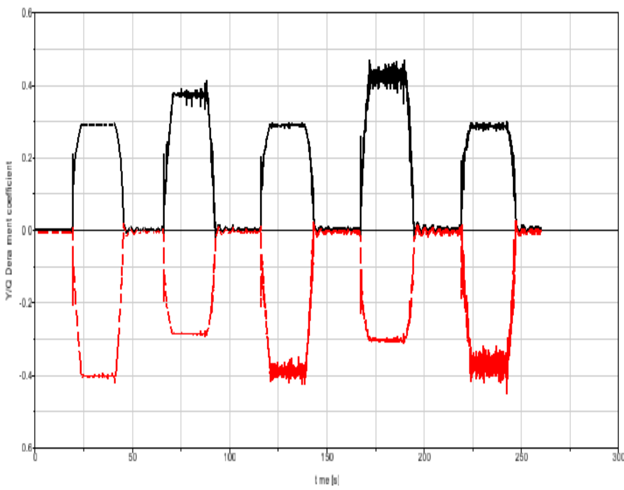


Fig.54 Quotient of lateral over vertical force (Y/Q)

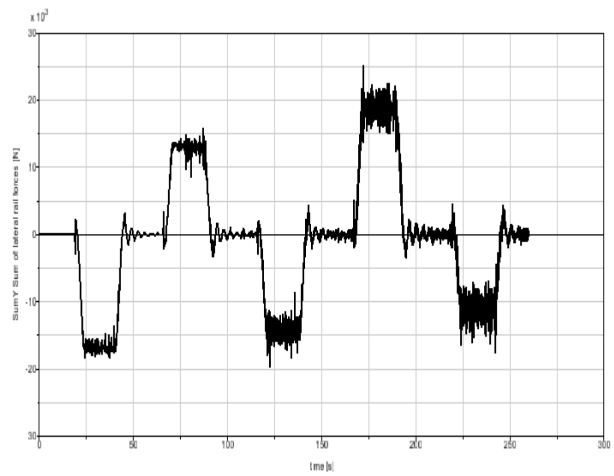


Fig.55 Sum of lateral forces wheelset 1

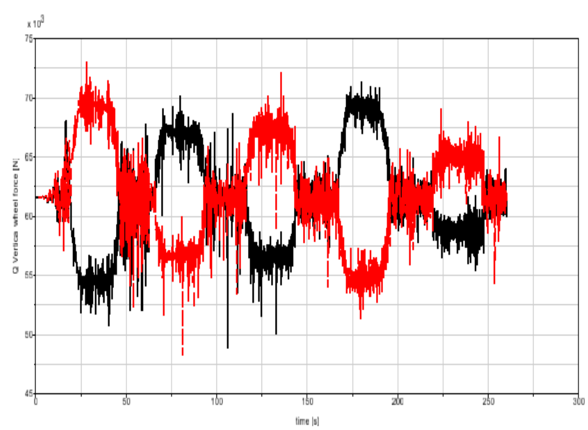


Fig.56 Vertical forces Q wheelset 2

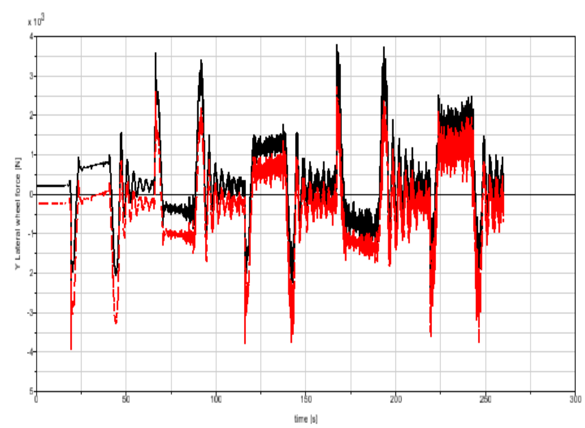
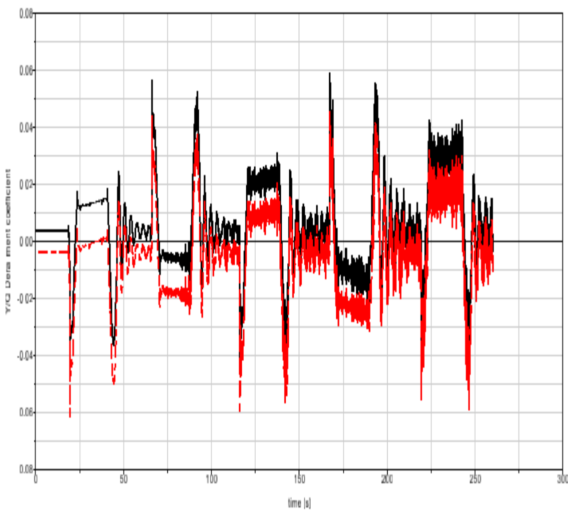


Fig.57 Lateral force Y wheelset 2



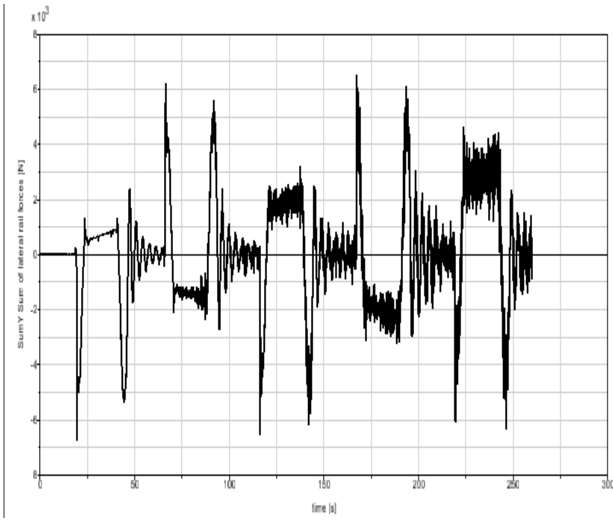
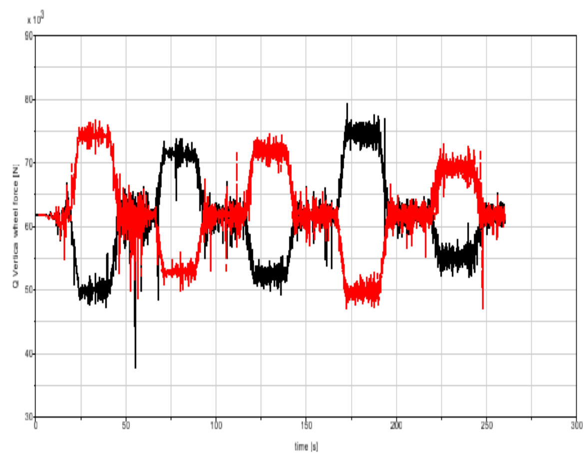


Fig.58 Quotient of lateral over vertical force (Y/Q) Fig.59 Sum of lateral forces wheelset 2



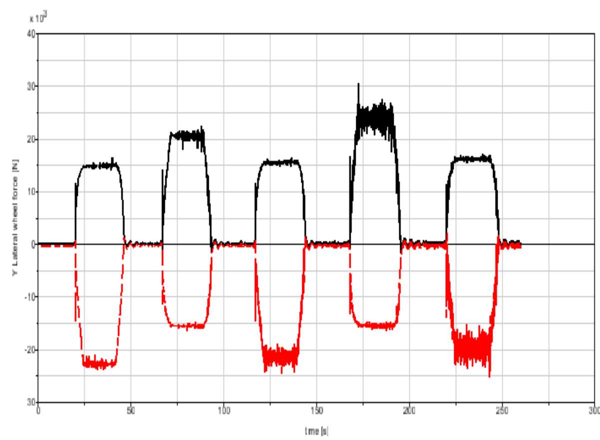
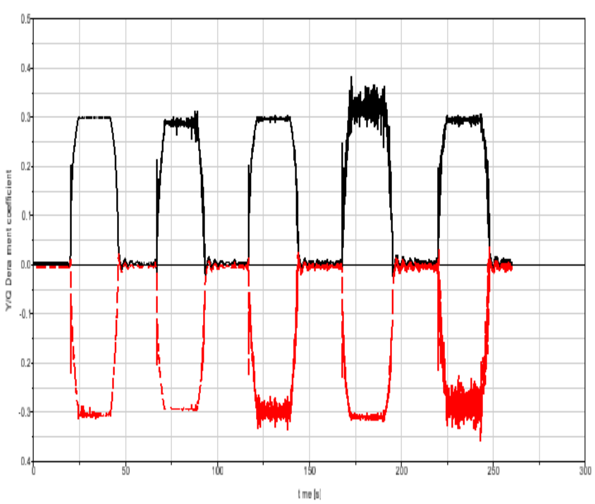


Fig.60 Vertical force Q wheelset 1

Fig.61 Lateral force Y wheelset 1



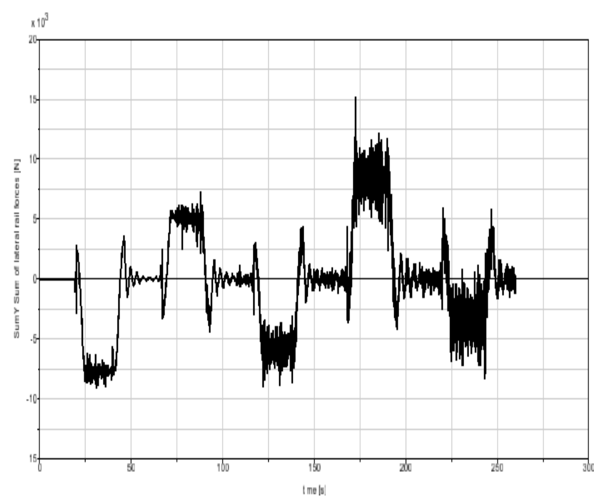


Fig.62 Quotient of lateral over vertical force (Y/Q) wheelset 1

Fig.63 Sum of lateral forces

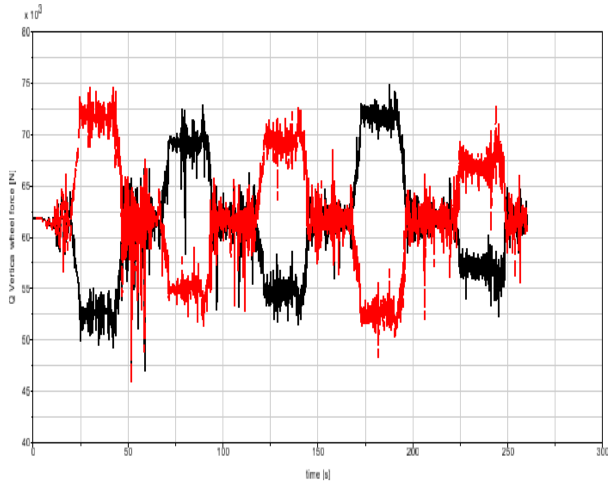


Fig.64 Vertical force Q wheelset 2

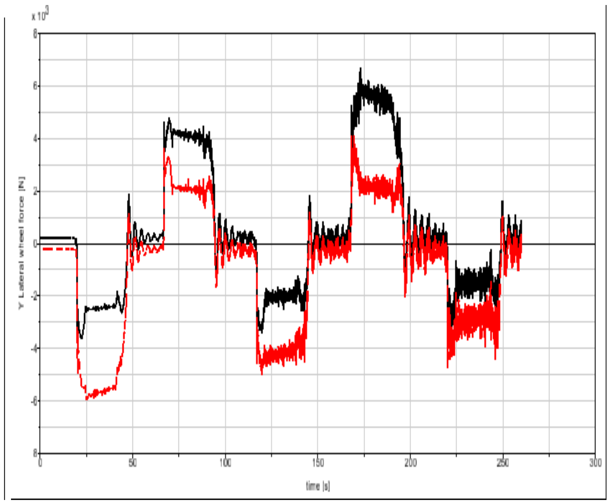


Fig.65 Lateral force Y wheelset 2

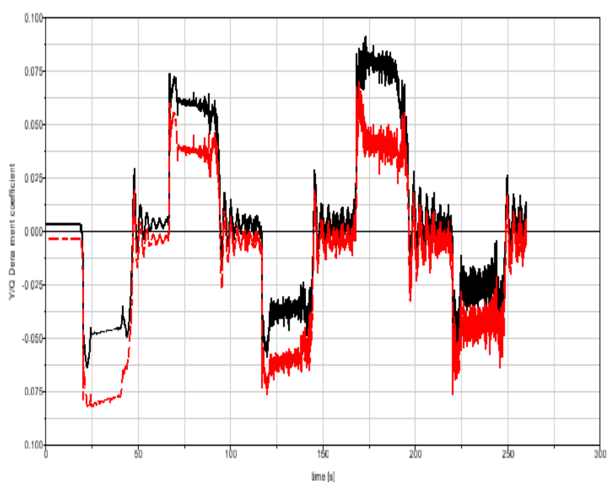


Fig.66 Quotient of lateral over vertical force (Y/Q)

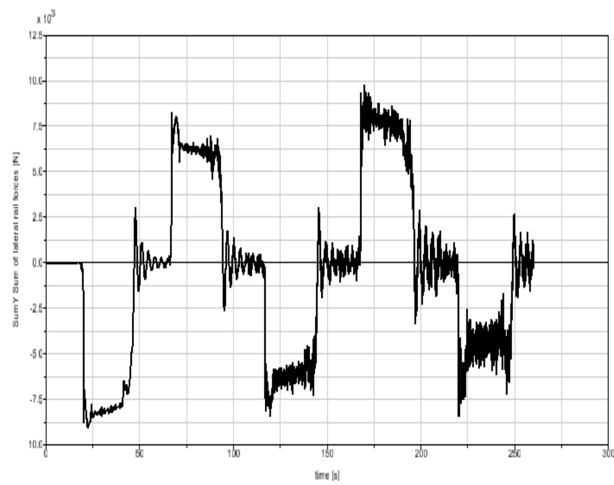


Fig.67 Sum of lateral force wheelset 2

ACCELERATIONS IN CAR-BODY :-

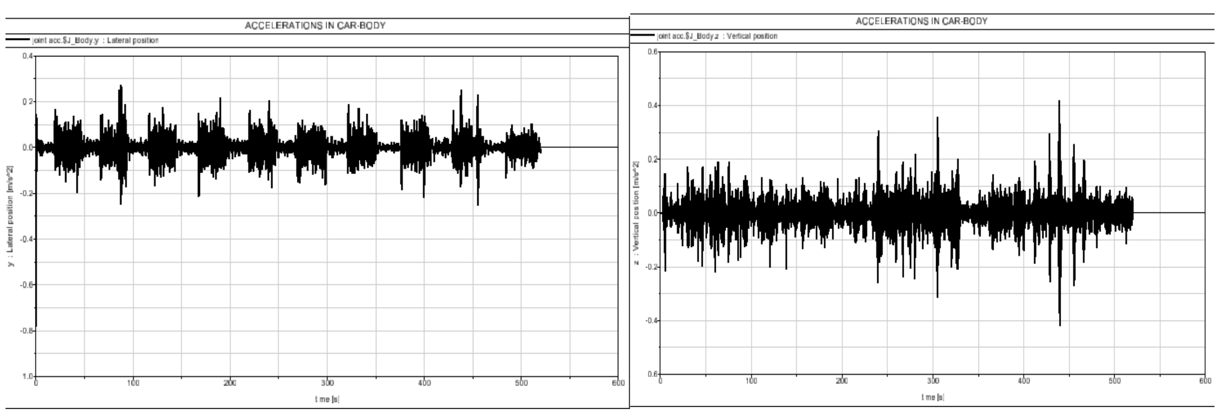


Fig.4.83 Lateral and vertical acceleration car-body

APPENDIX B :-

ANALYSIS ON FILTERING OF RESULTS

Test Zone 1 :- Bogie Front Wheelset 1

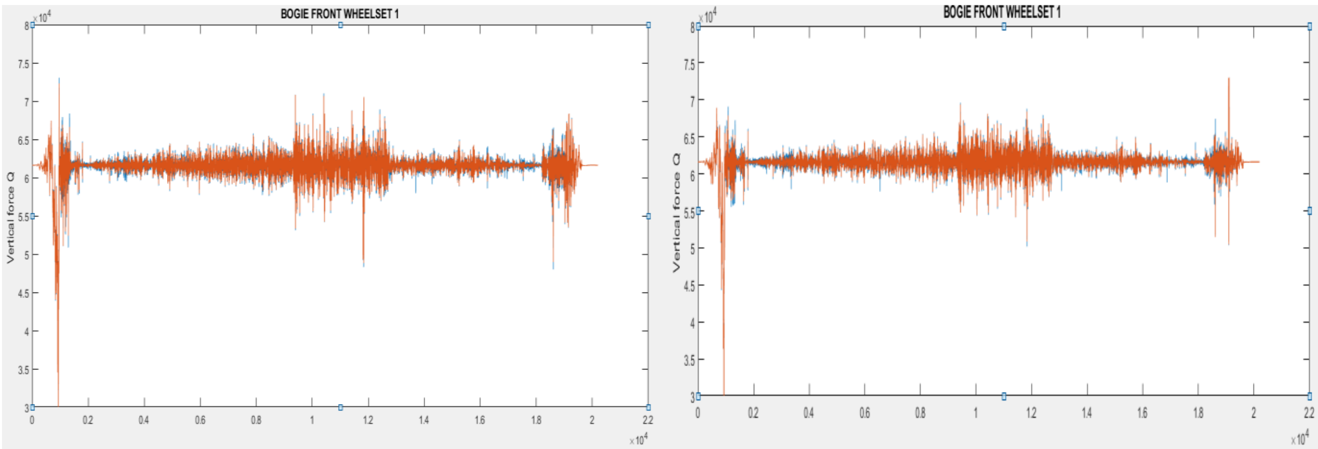


Fig.1 Vertical force Q

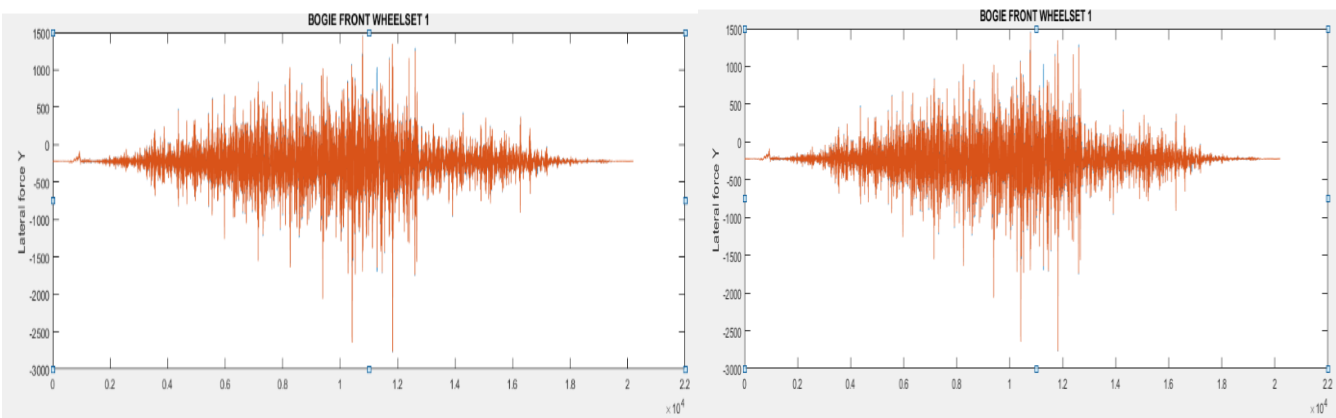


Fig.2 Lateral force Y

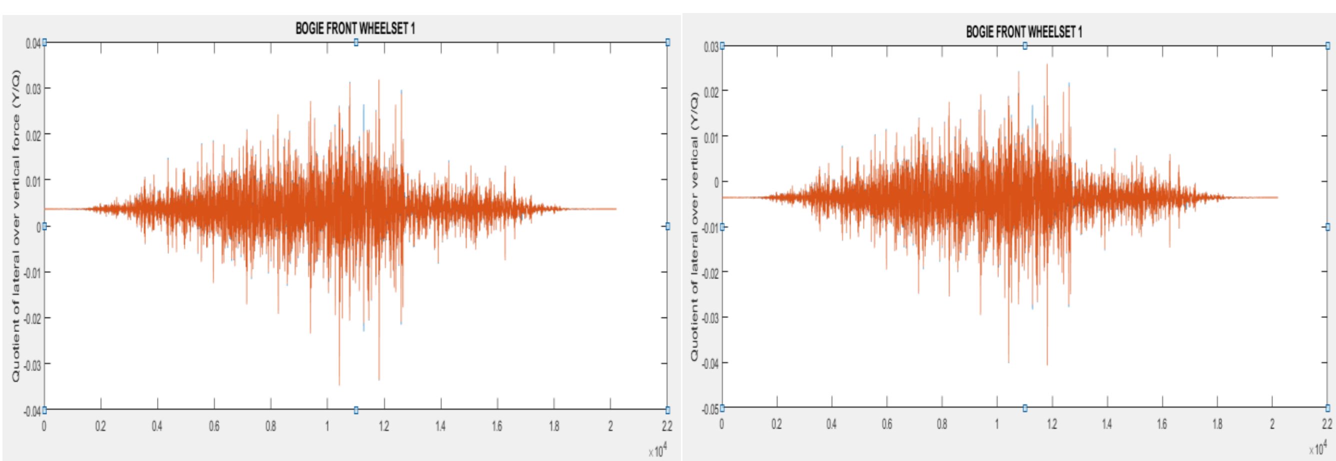


Fig.3 Quotient of lateral over vertical force (Y/Q)

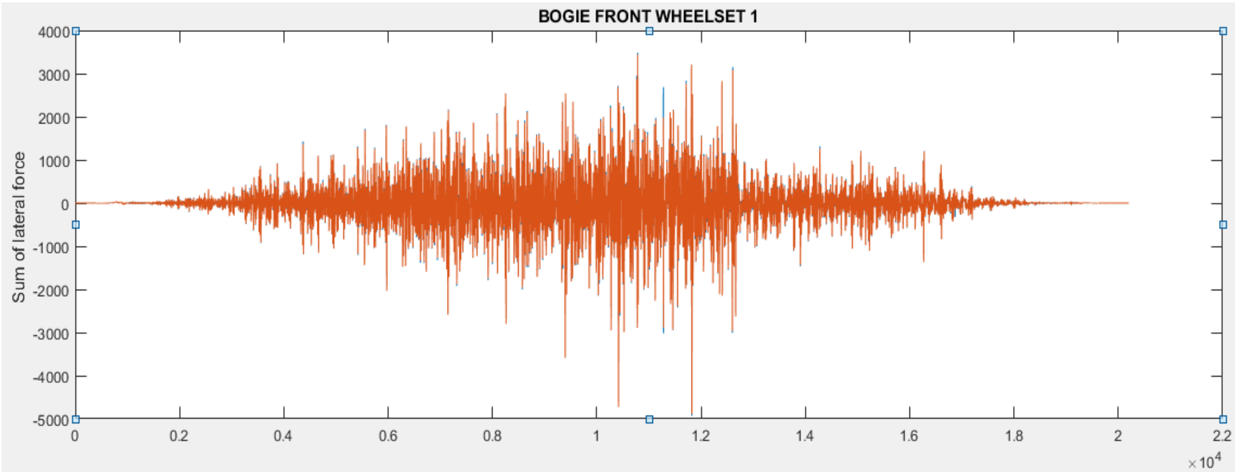


Fig.4 Sum of lateral force wheelset 1

BOGIE FRONT WHEELSET 2 :-

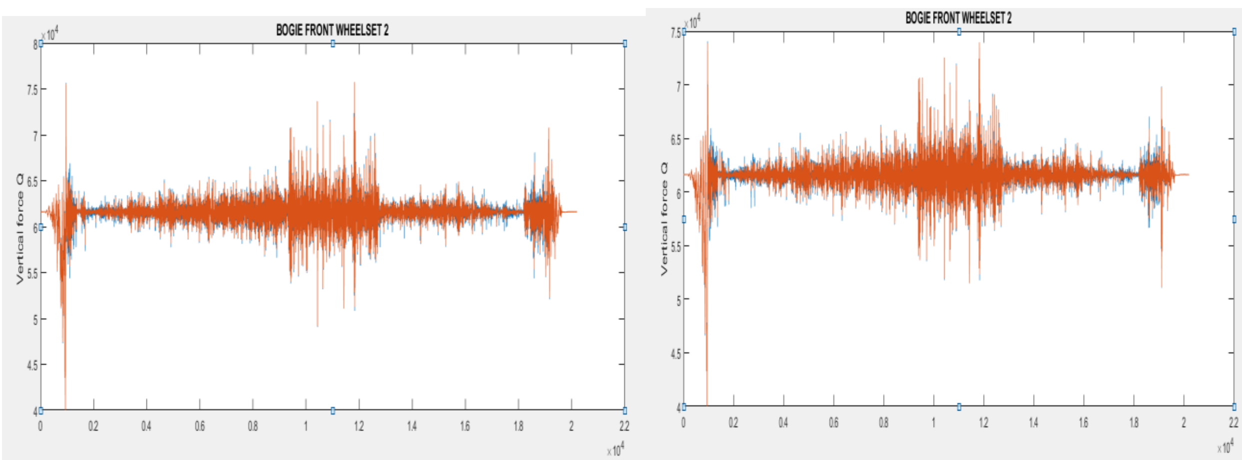


Fig.5 Vertical force Q

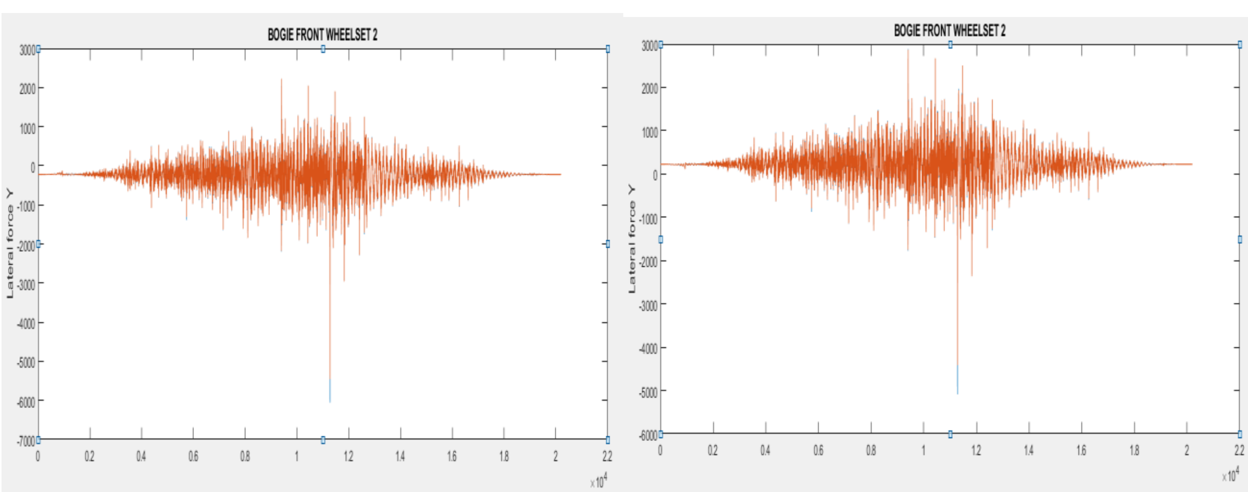


Fig.6 Lateral force Y

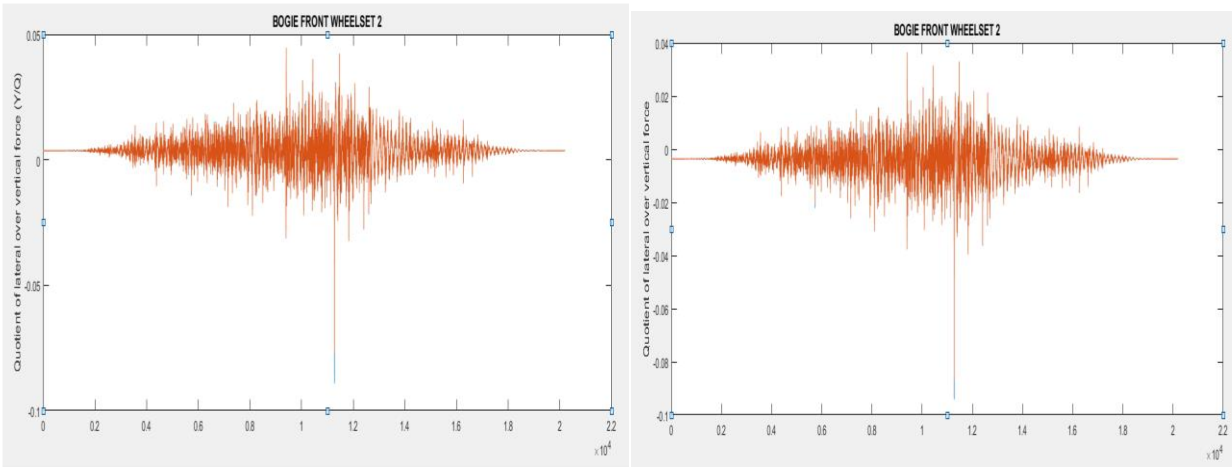


Fig.7 Quotient of lateral over vertical force (Y/Q)

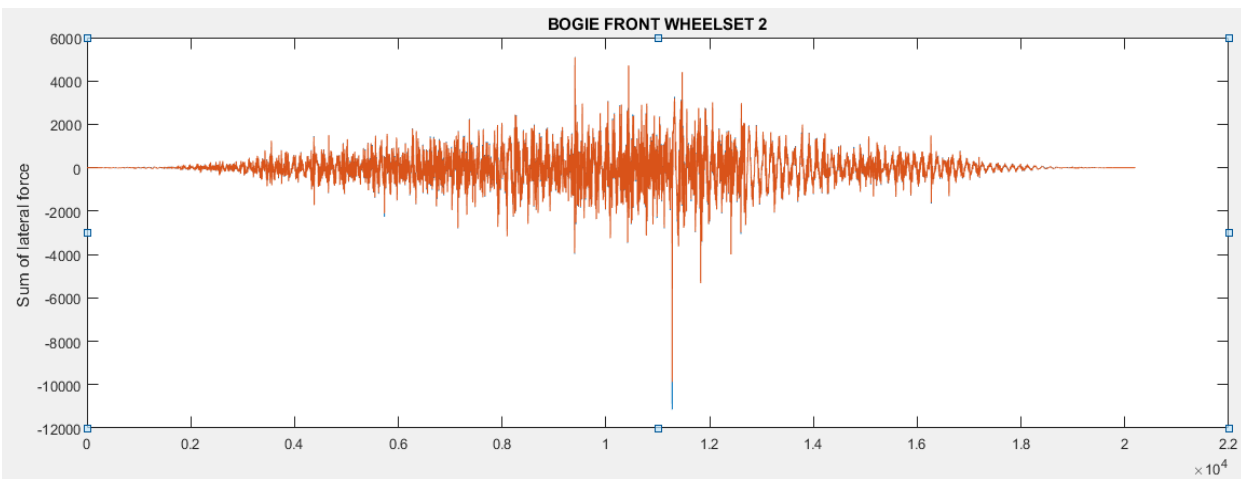


Fig.8 Sum of lateral forces

BOGIE REAR WHEELSET 1 :-

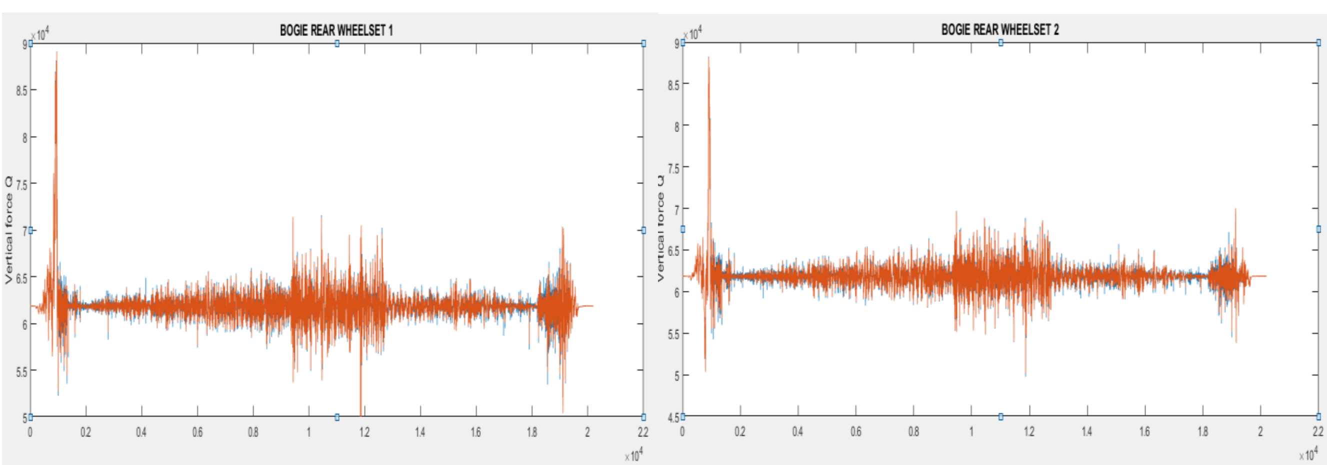


Fig.9 Vertical force Q

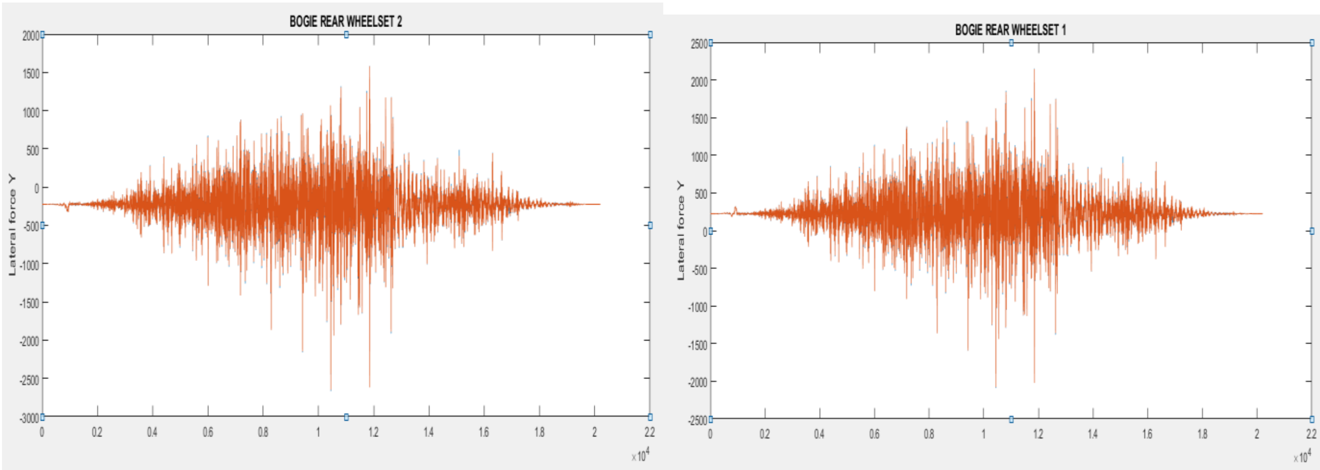


Fig.10 Lateral force Y

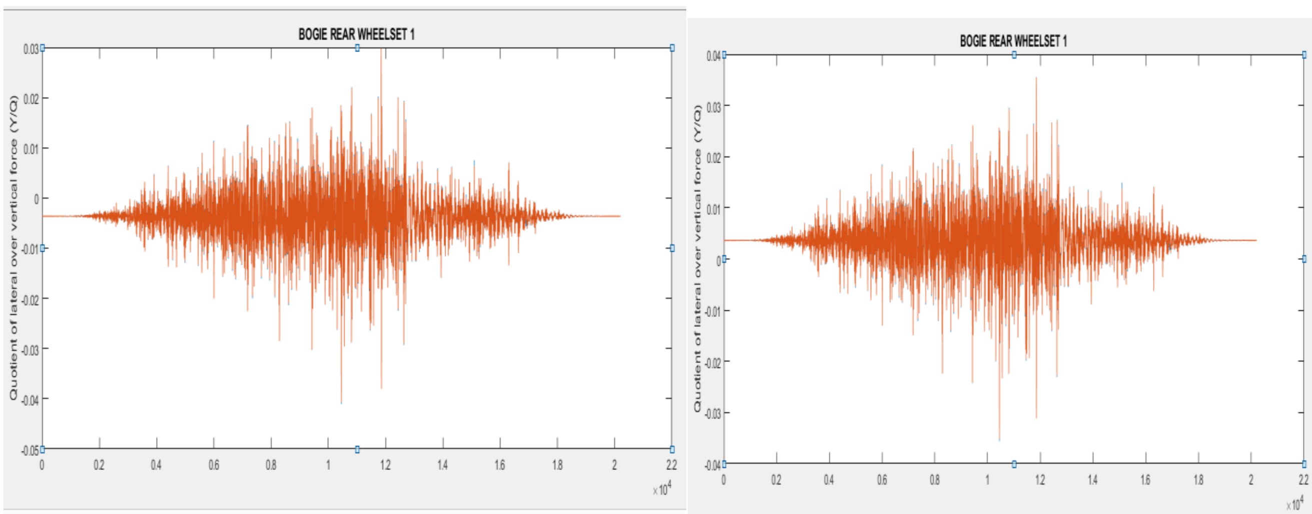


Fig.11 Quotient of lateral over vertical force (Y/Q)

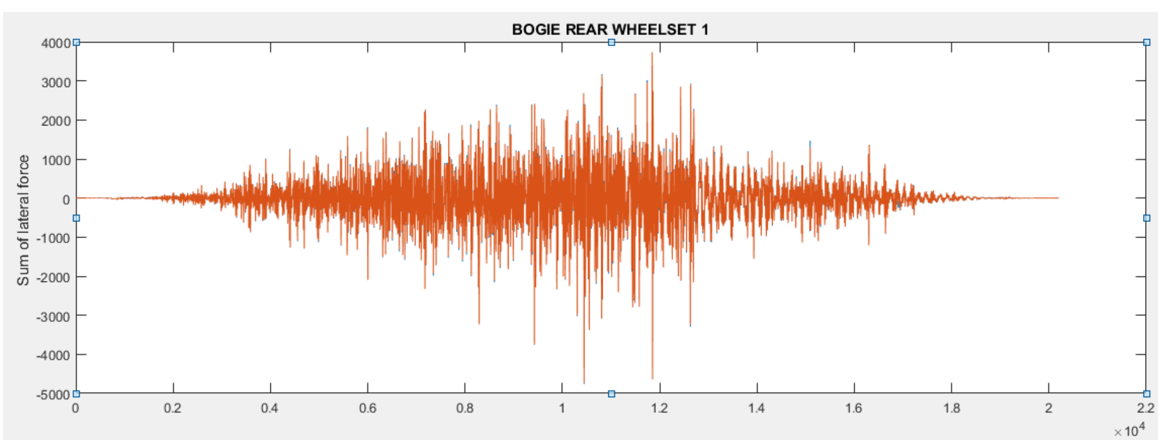


Fig.12 Sum of lateral force wheelset 1

BOGIE REAR WHEELSET 2 :-

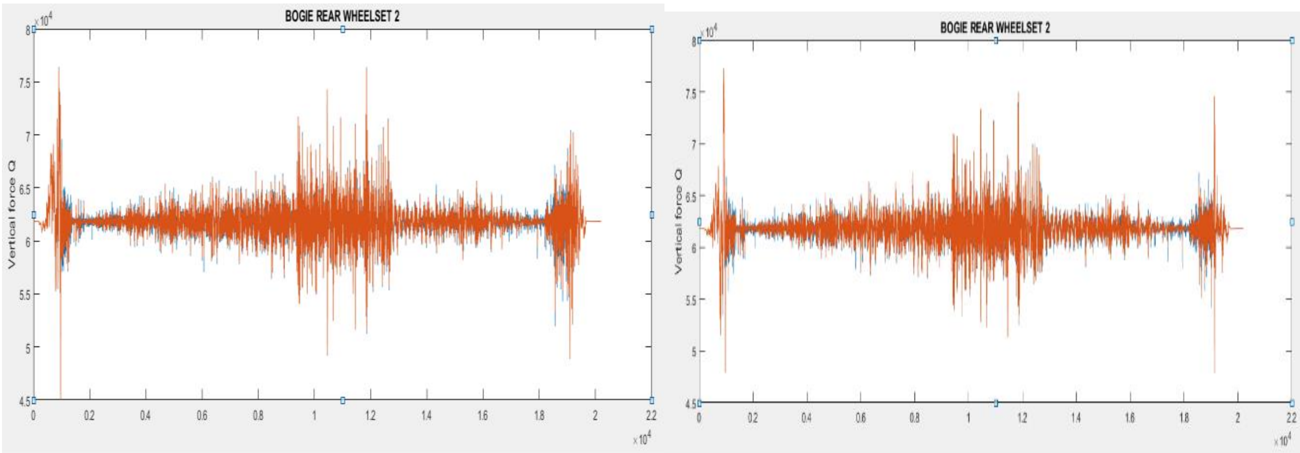


Fig.13 Vertical force Q

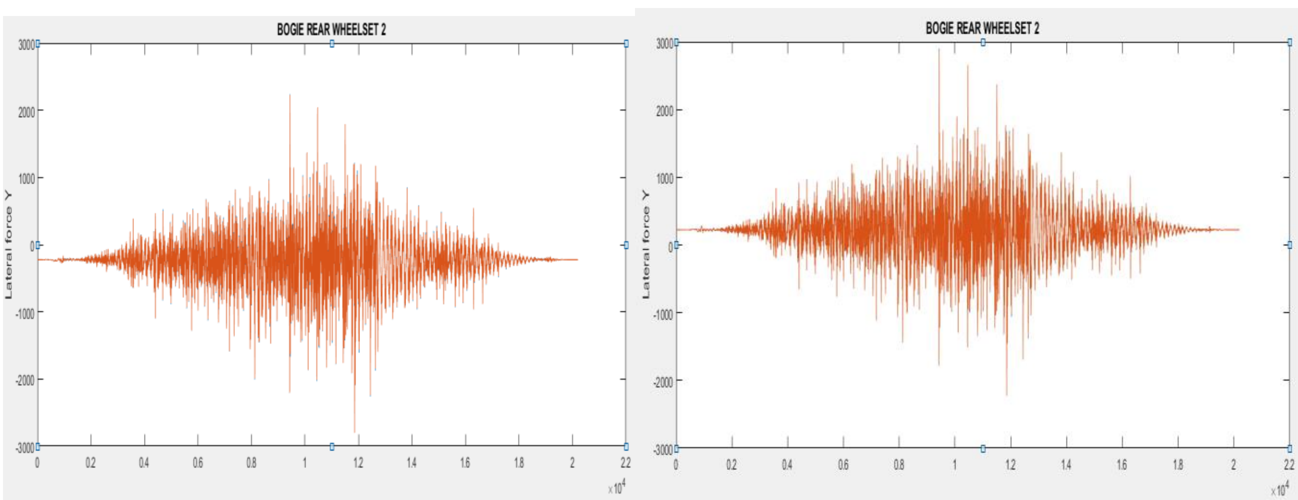


Fig.14 Lateral force Y

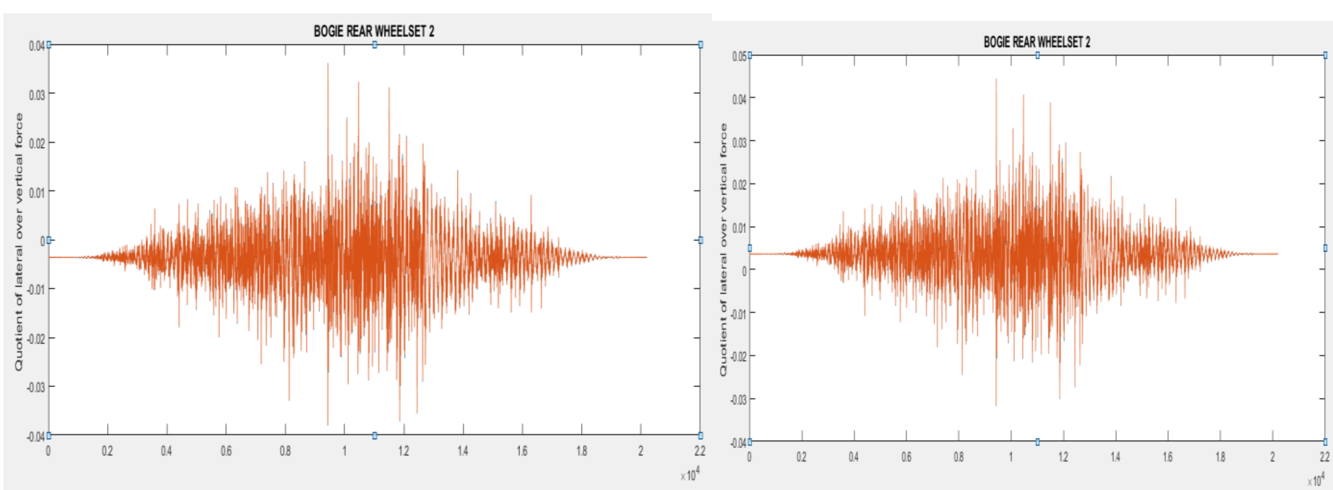


Fig.15 Quotient of lateral over vertical force (Y/Q)

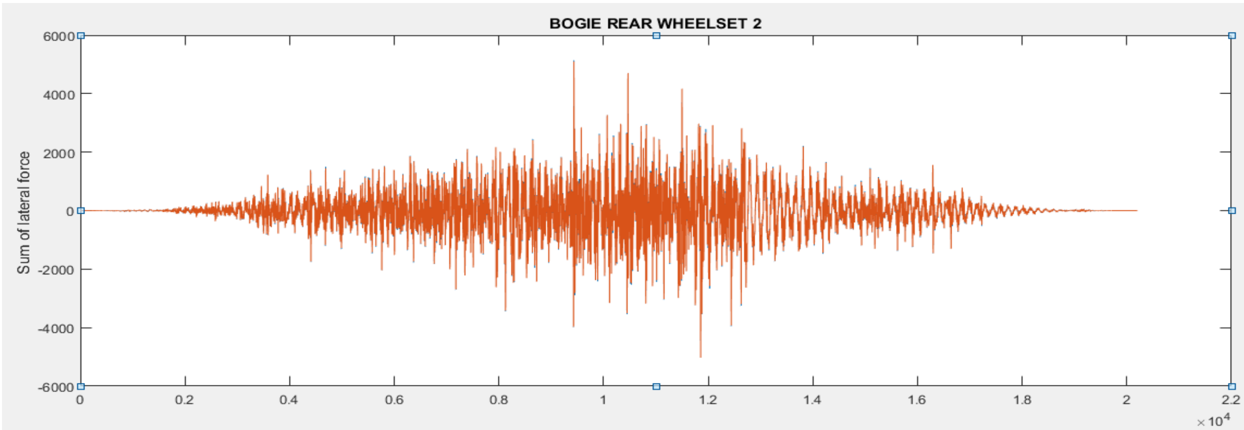


Fig.16 Sum of lateral forces wheelset 2

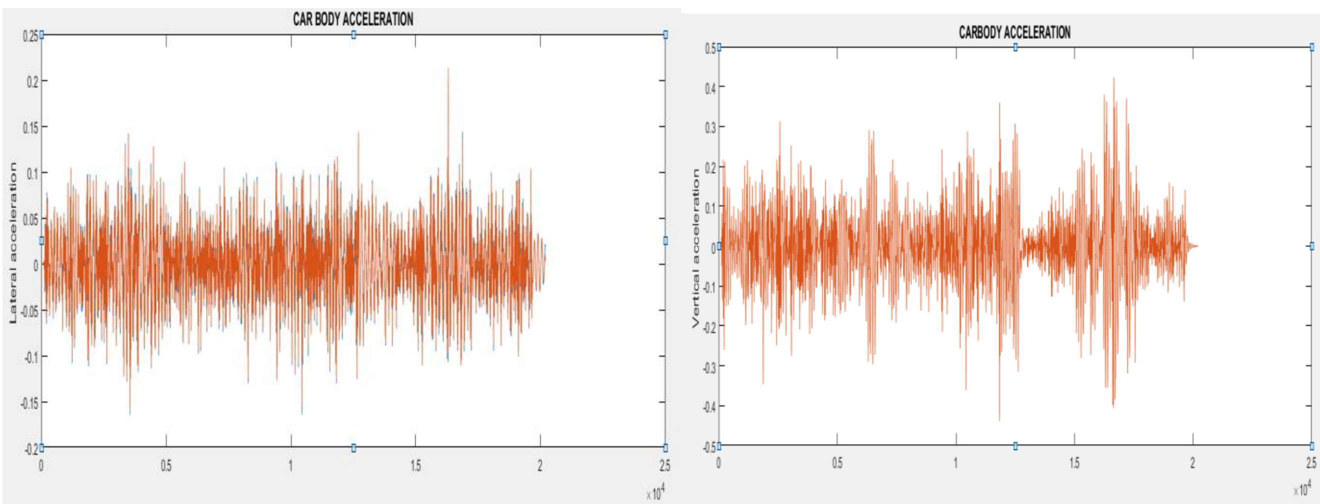


Fig.17 Car-body acceleration

Filtering Results Test Zone 2 :-

Bogie Front Wheelset 1 :-

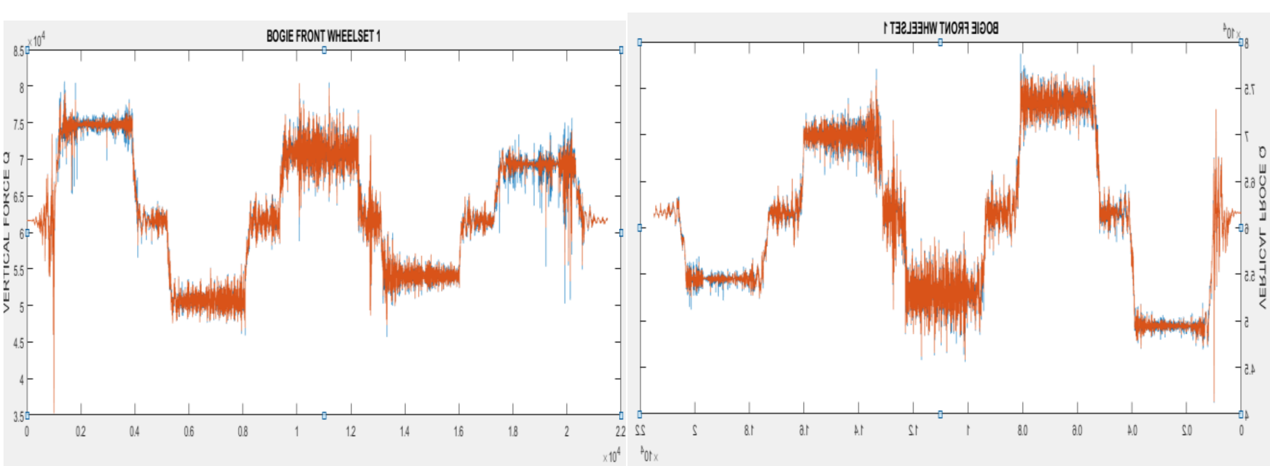


Fig.18 Vertical force Q

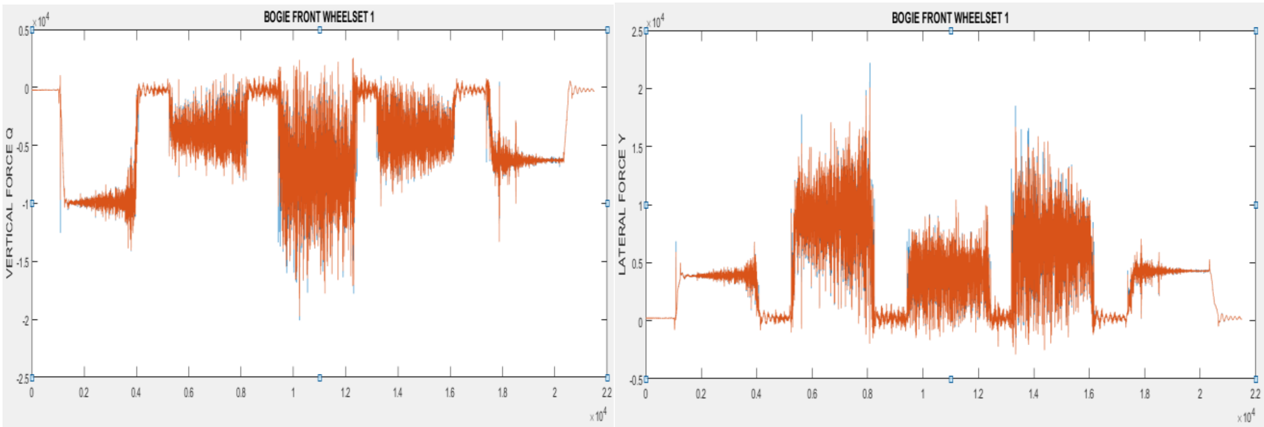


Fig.19 Lateral force Y

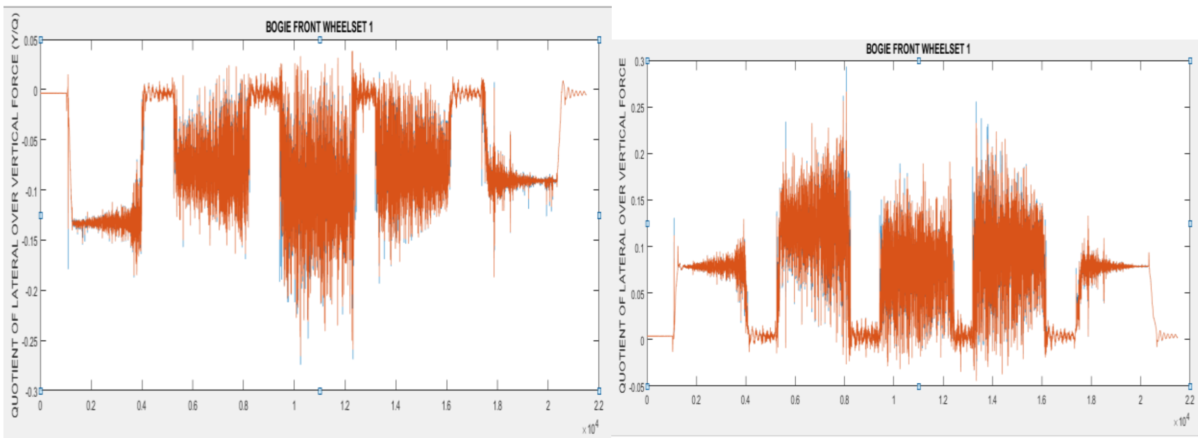


Fig.20 Quotient of lateral over vertical force (Y/Q)

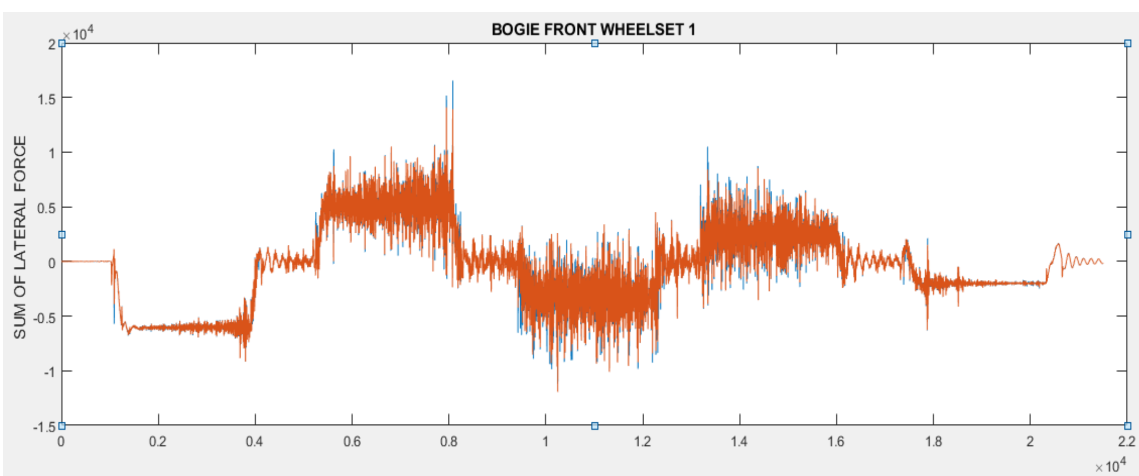


Fig.21 Sum of lateral forces

BOGIE FRONT WHEELSET 2 :-

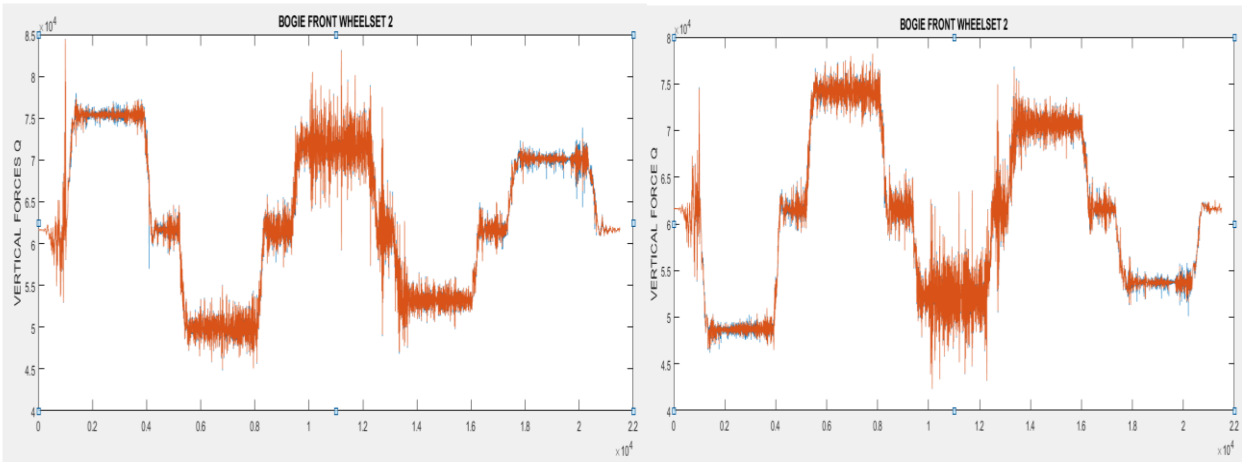


Fig.22 Vertical force Q

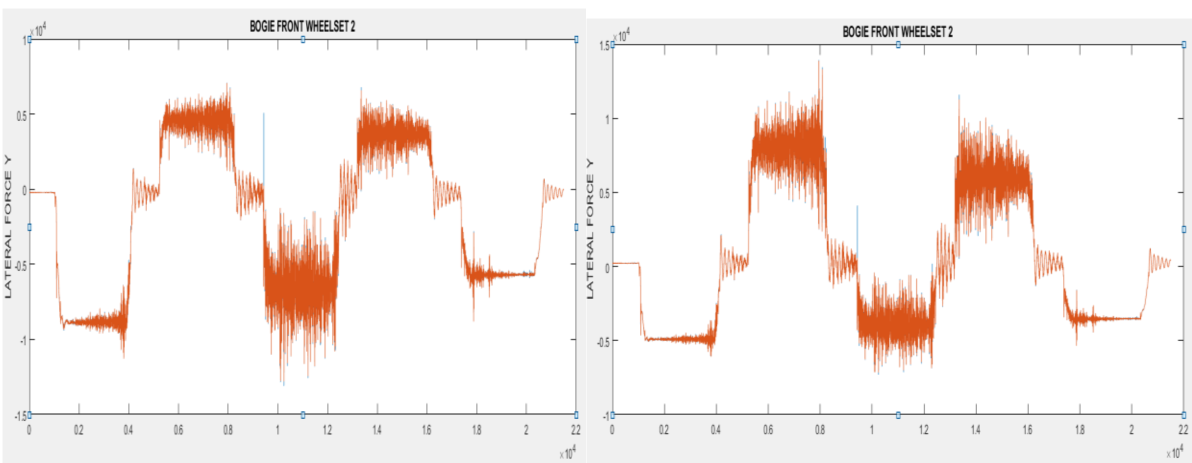


Fig.23 Lateral force Y

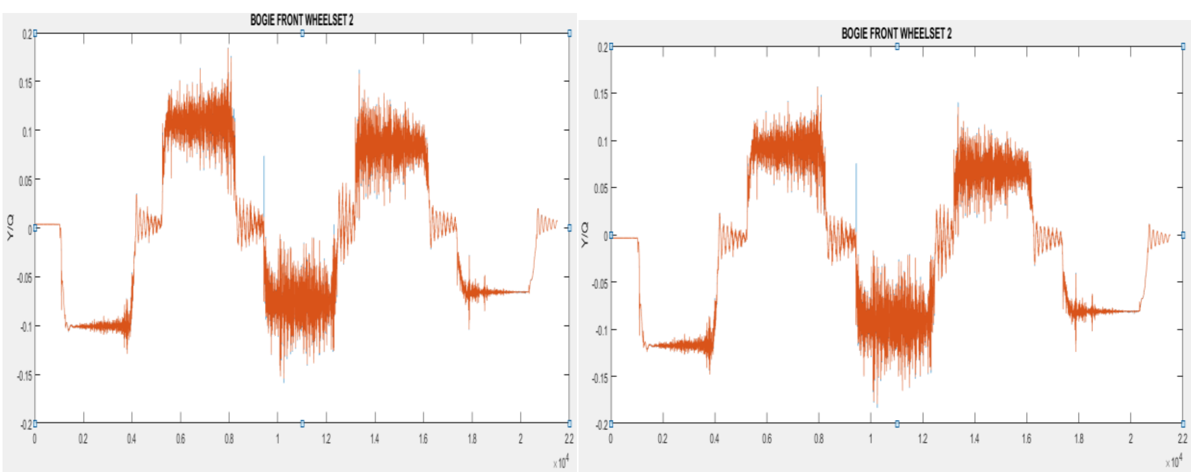


Fig.24 Quotient of lateral over vertical forces

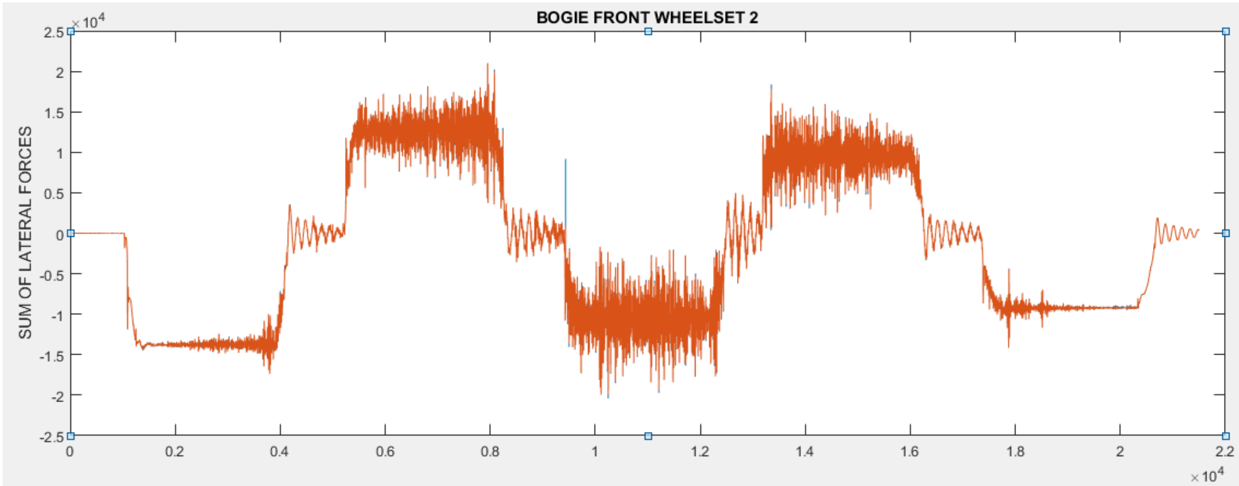
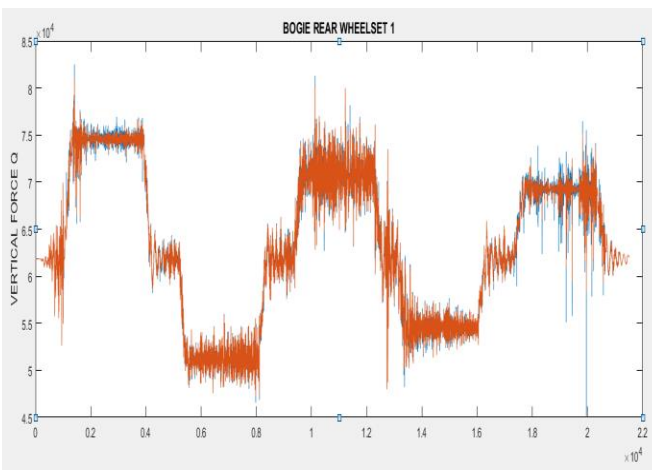


Fig.25 Sum of lateral forces

BOGIE REAR WHEELSET 1 :-



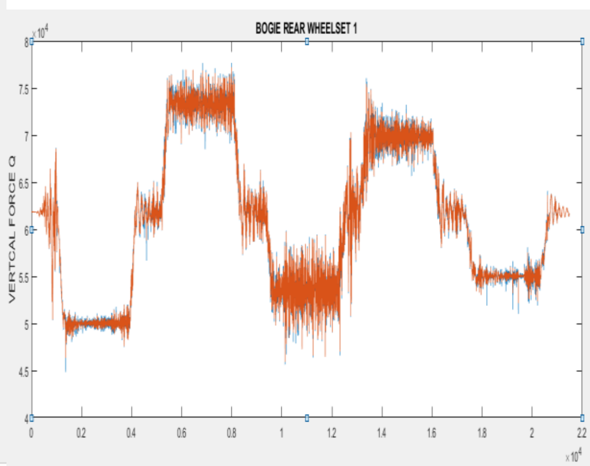
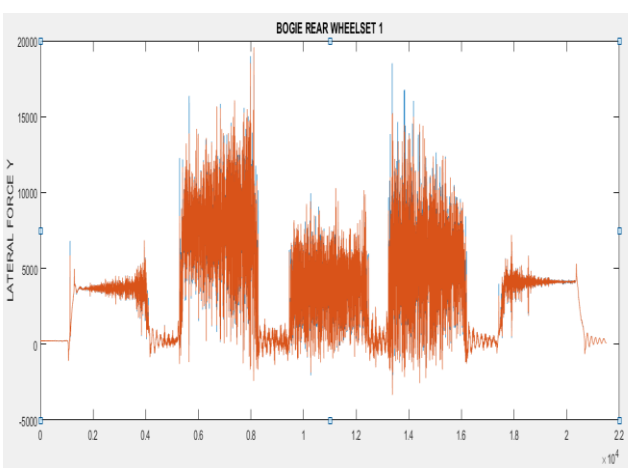


Fig.26 Vertical force Q



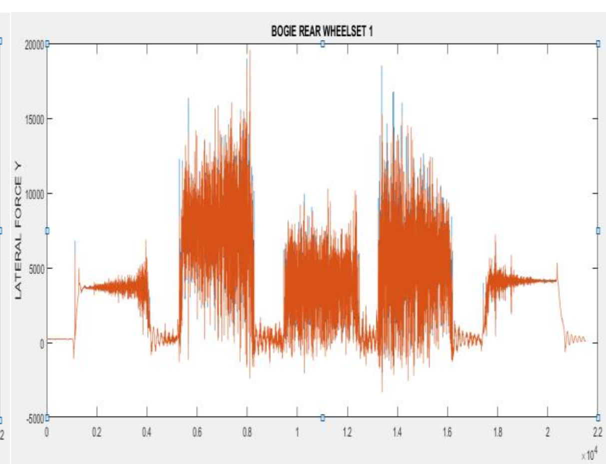


Fig.27 Lateral force Y

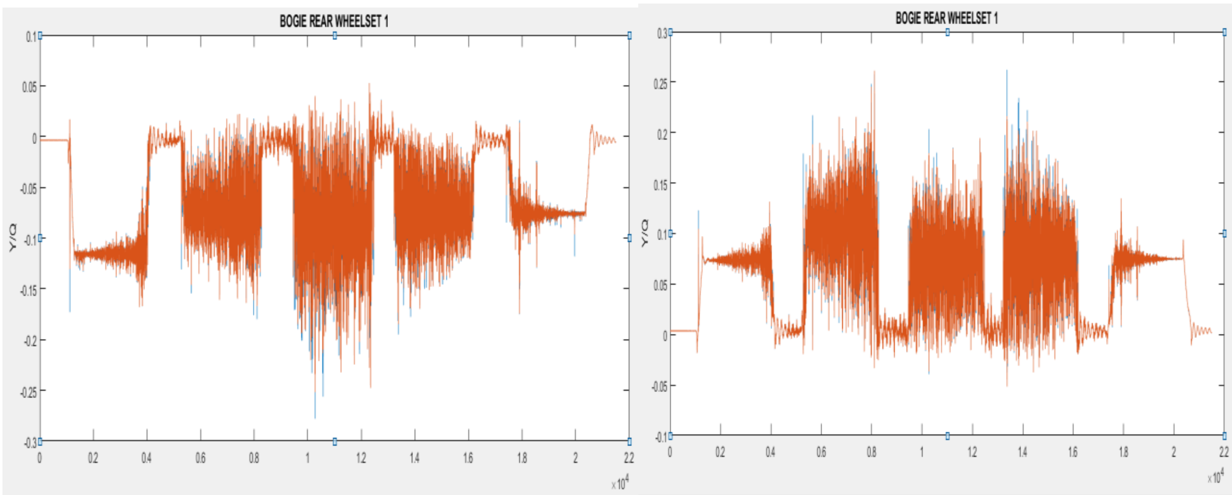


Fig.28 Quotient of lateral over vertical forces (Y/Q)

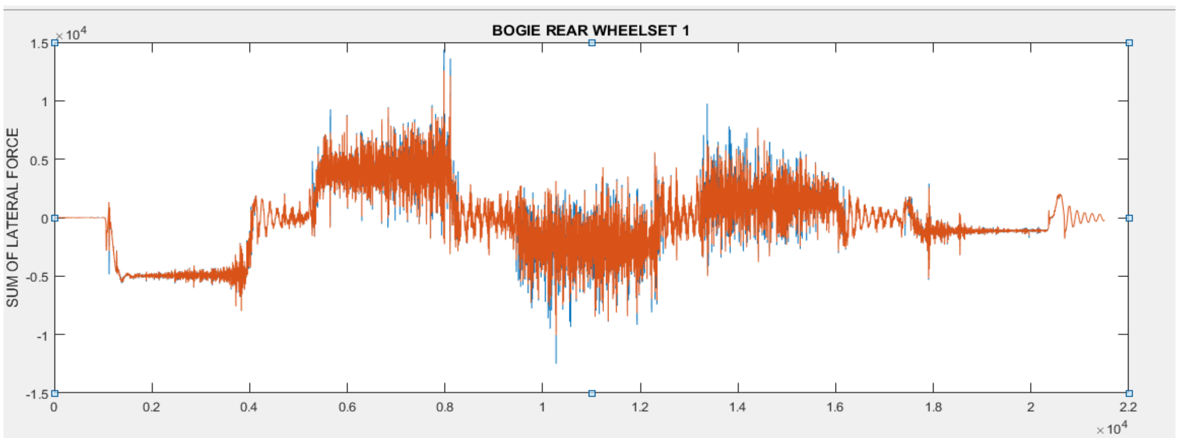


Fig.29 Sum of lateral forces

BOGIE REAR WHEELSET 2 :-

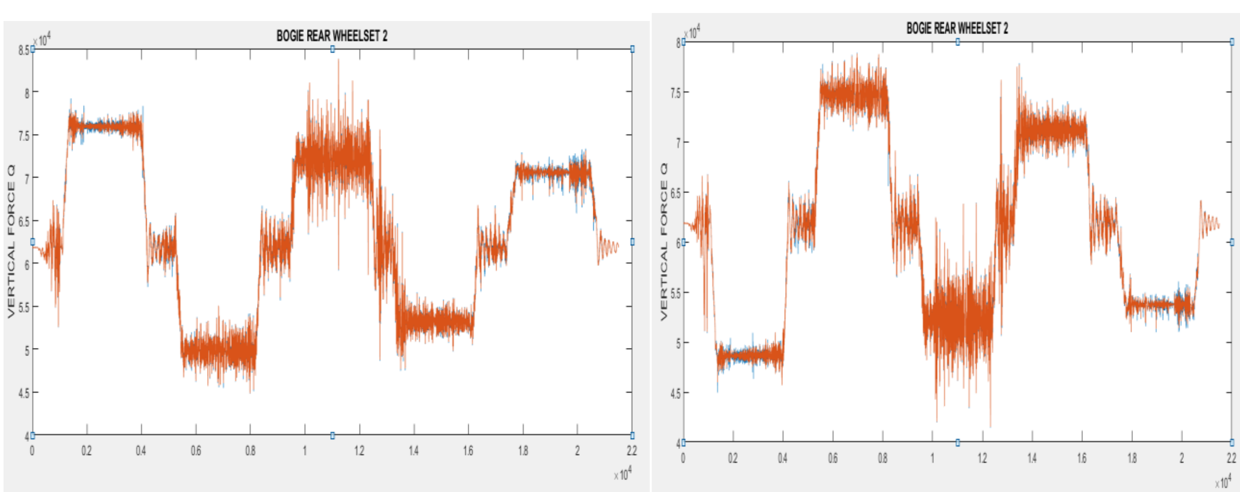


Fig.30 Vertical force Q

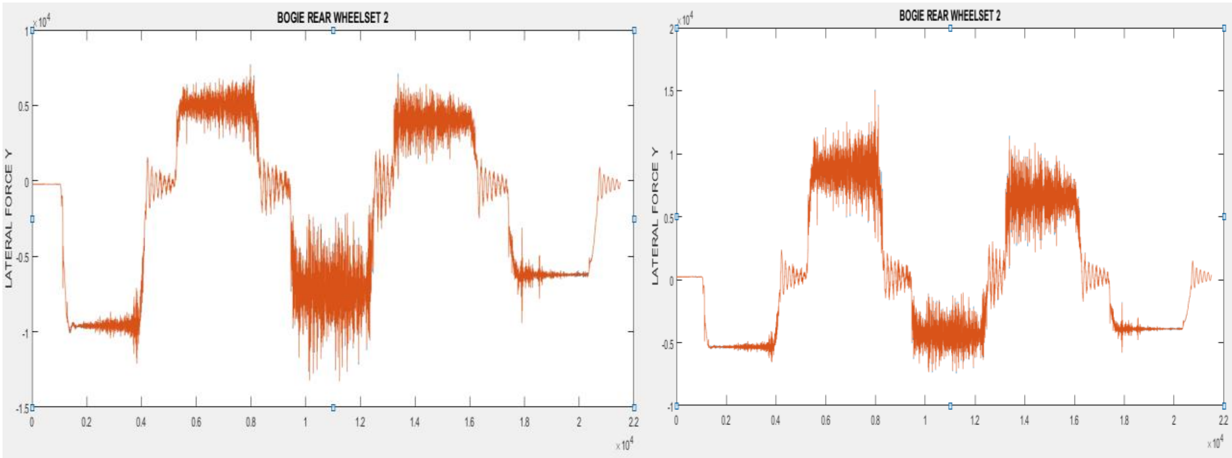


Fig.31 Lateral force Y

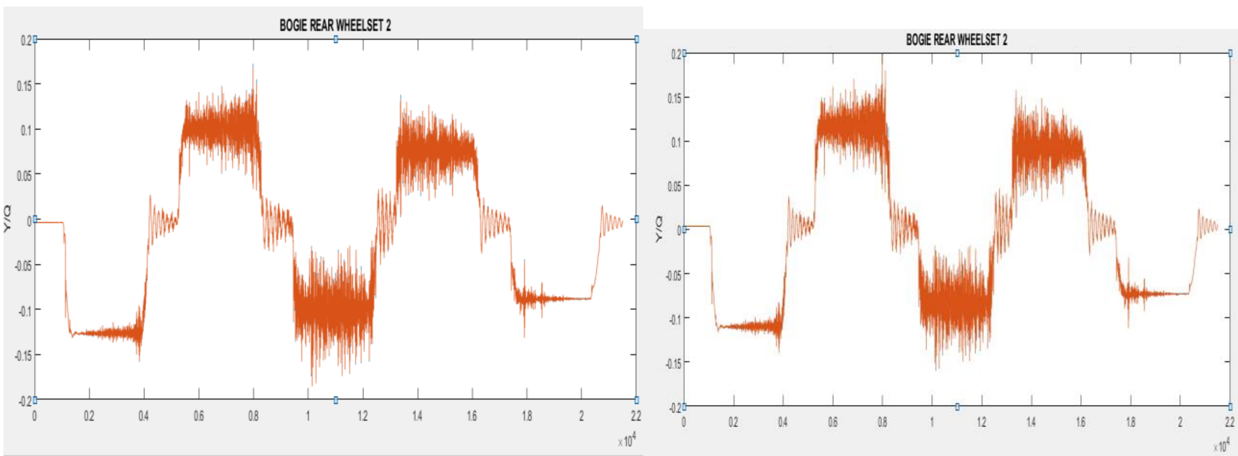


Fig.32 Quotient of lateral over vertical force

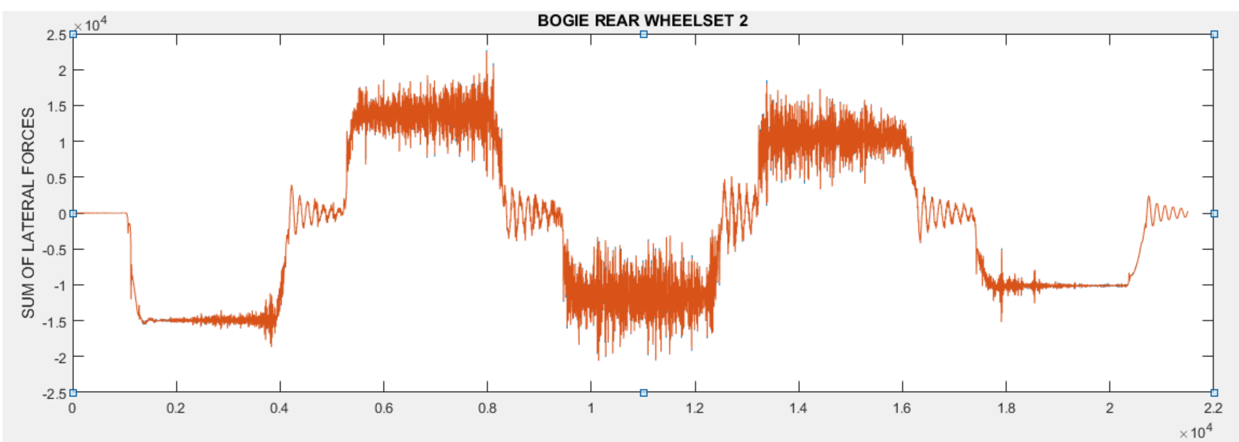


Fig.33 Sum of lateral forces

ACCELERATIONS IN CAR-BODY :-

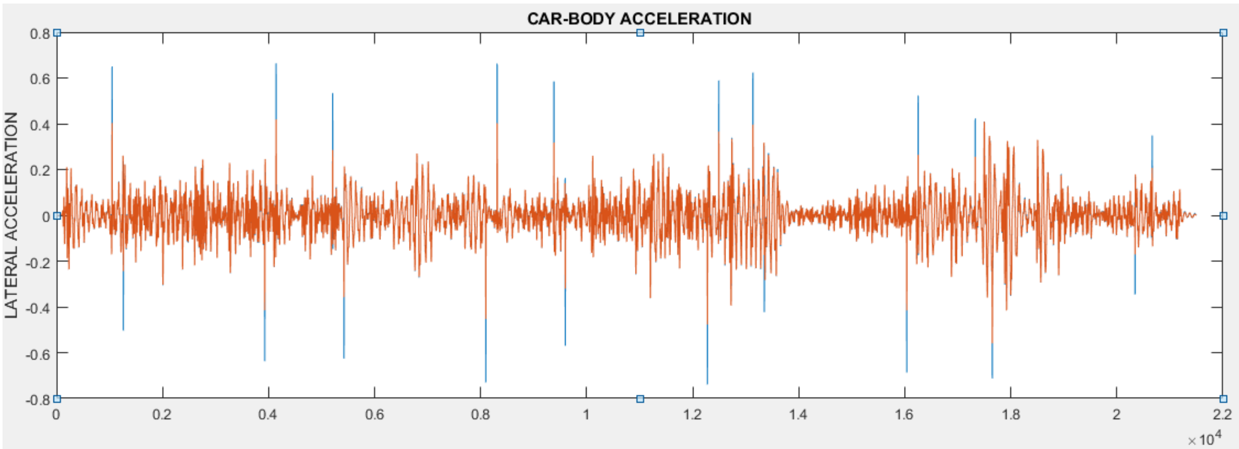


Fig.34 Lateral acceleration

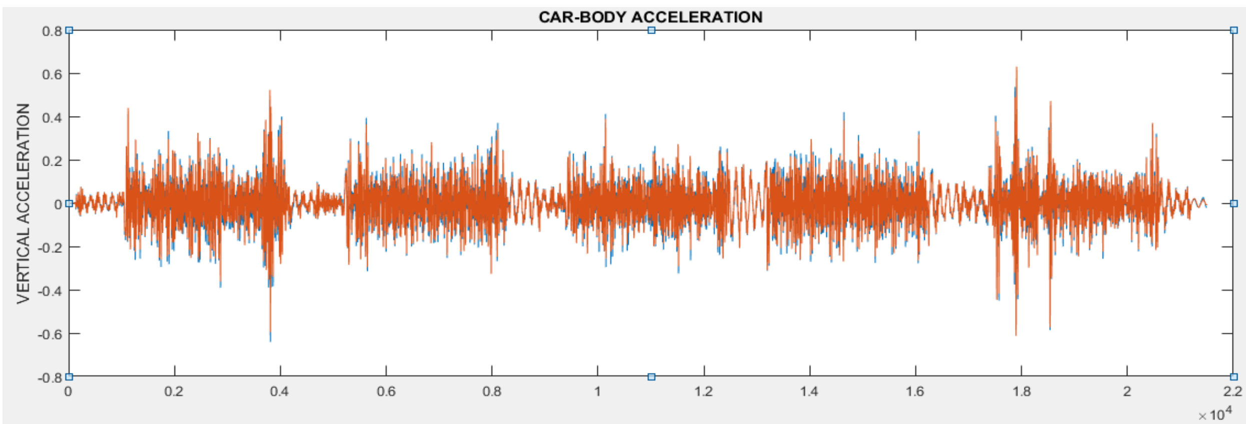


Fig.35 Vertical acceleration

Filtering Results on Test Zone 3 :-

BOGIE FRONT WHEELSET 1 :-

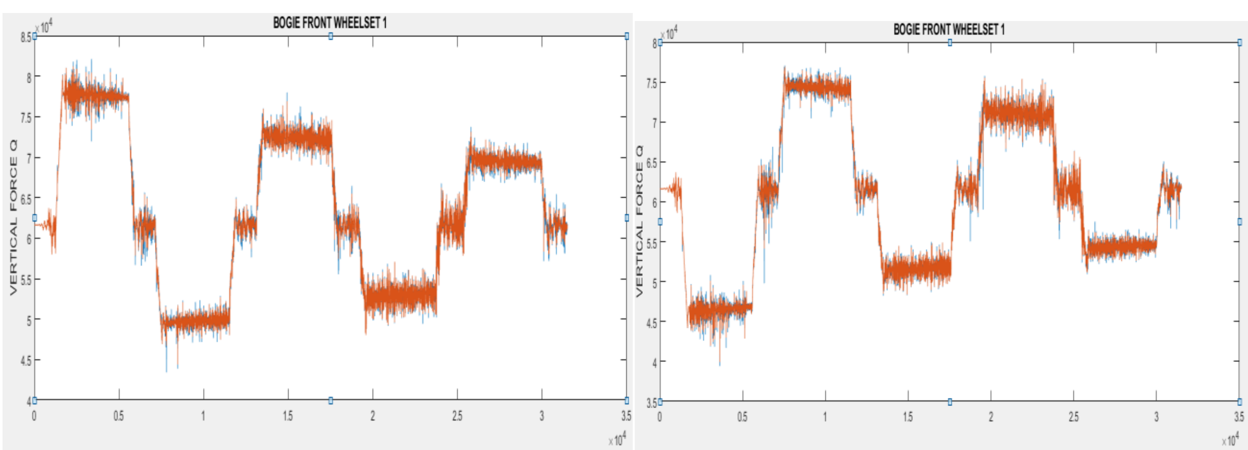


Fig.36 Vertical forces Q

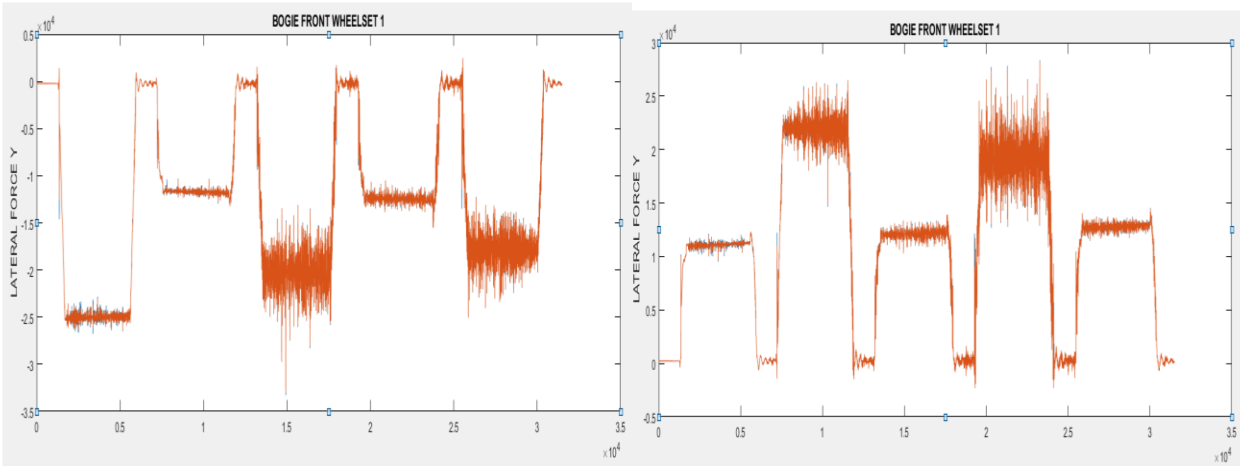


Fig.37 Lateral forces Y

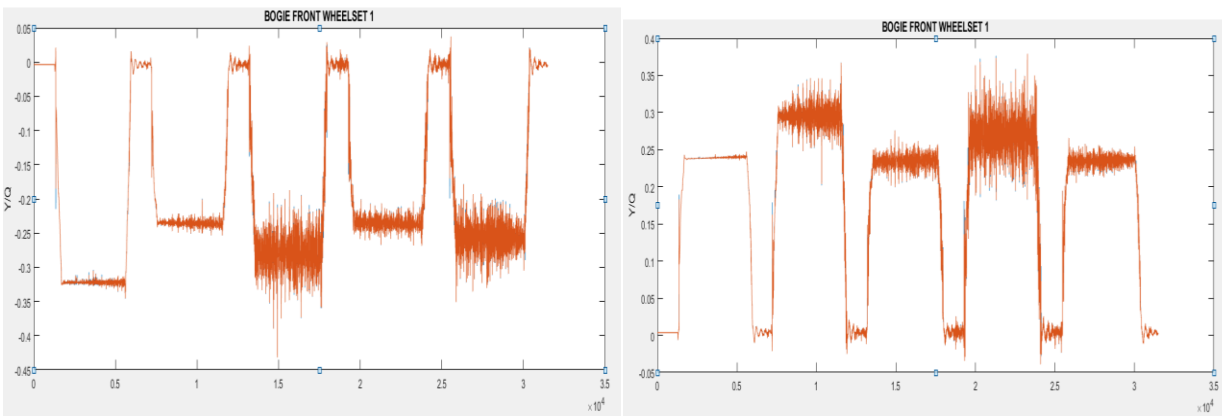


Fig.38 Quotient of lateral over vertical forces

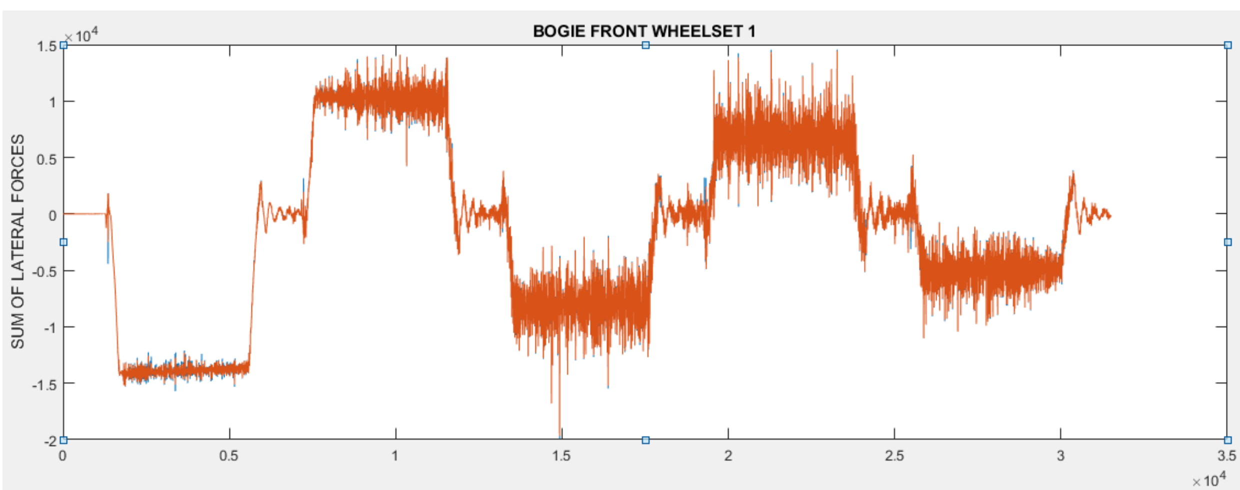


Fig.39 Sum of lateral forces

BOGIE FRONT WHEELSET 2 :-

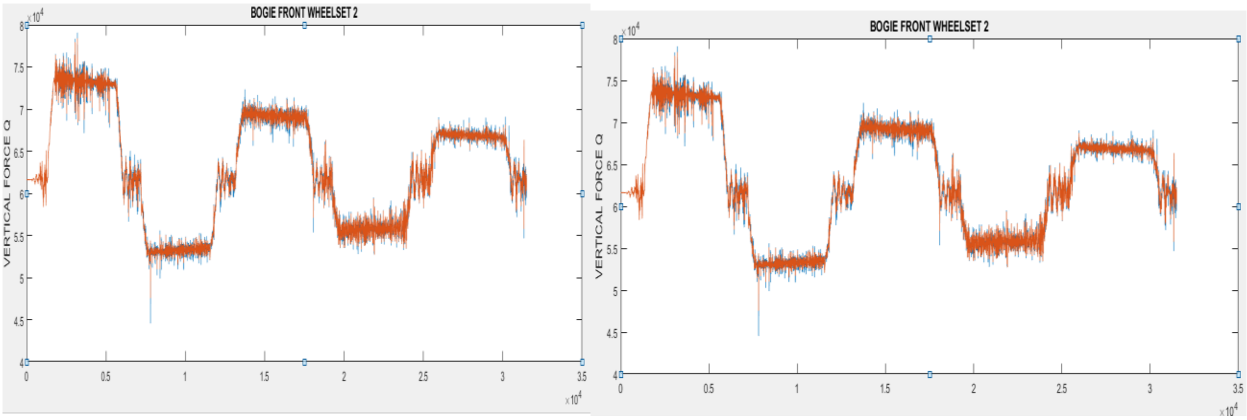


Fig.40 Vertical force Q

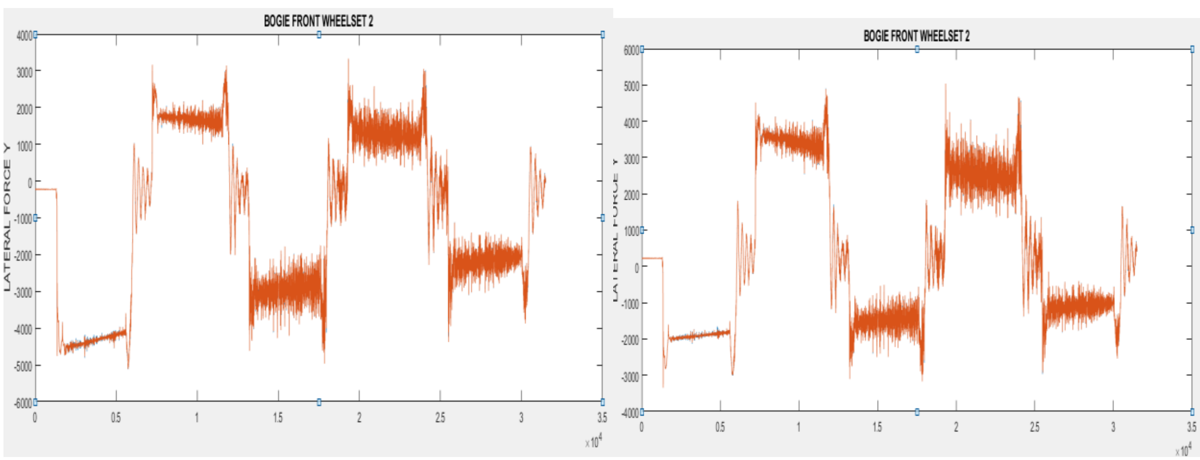


Fig.41 Lateral force Y

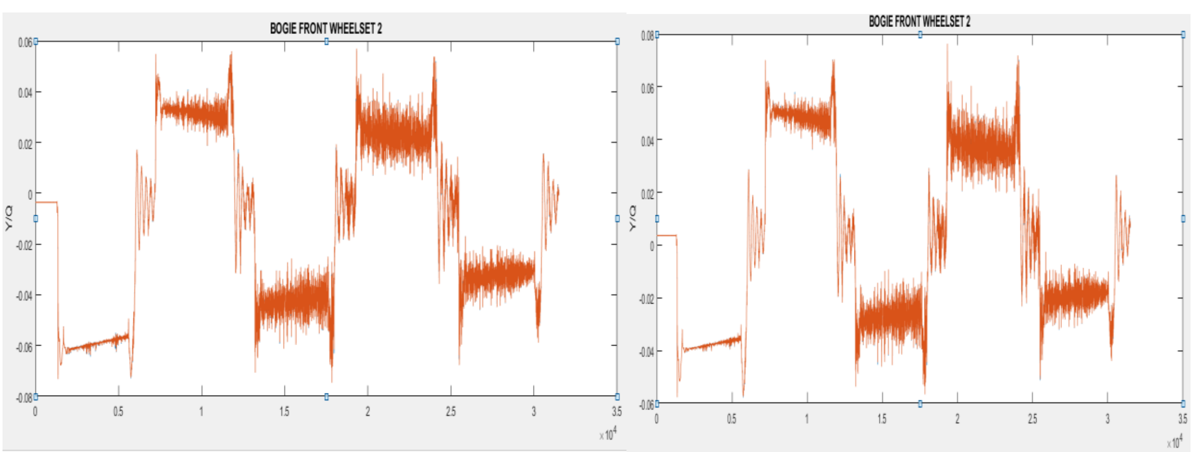


Fig.42 Quotient of lateral over vertical forces

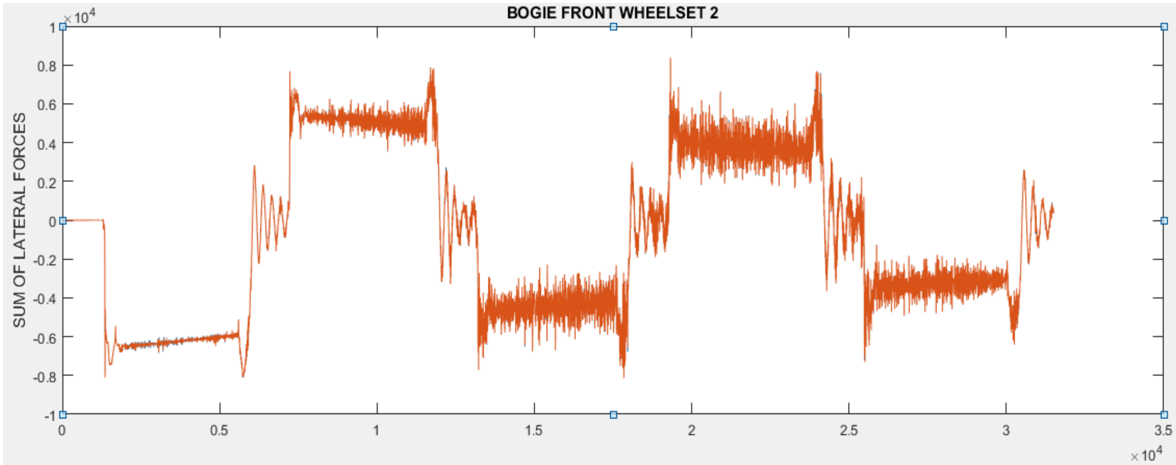


Fig.43 Sum of lateral forces

BOGIE REAR WHEELSET 1 :-

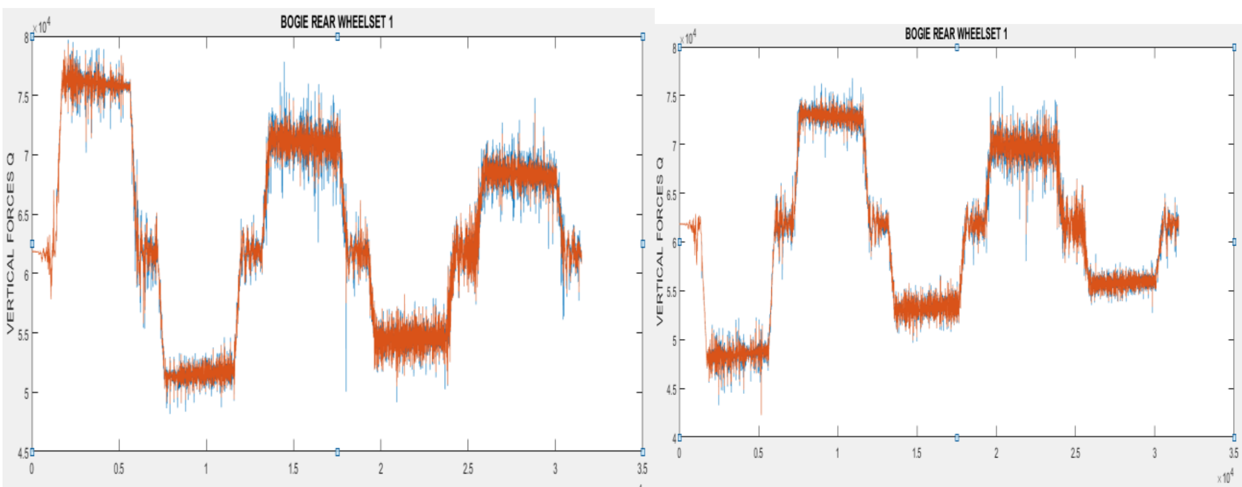


Fig.44 Vertical forces Q

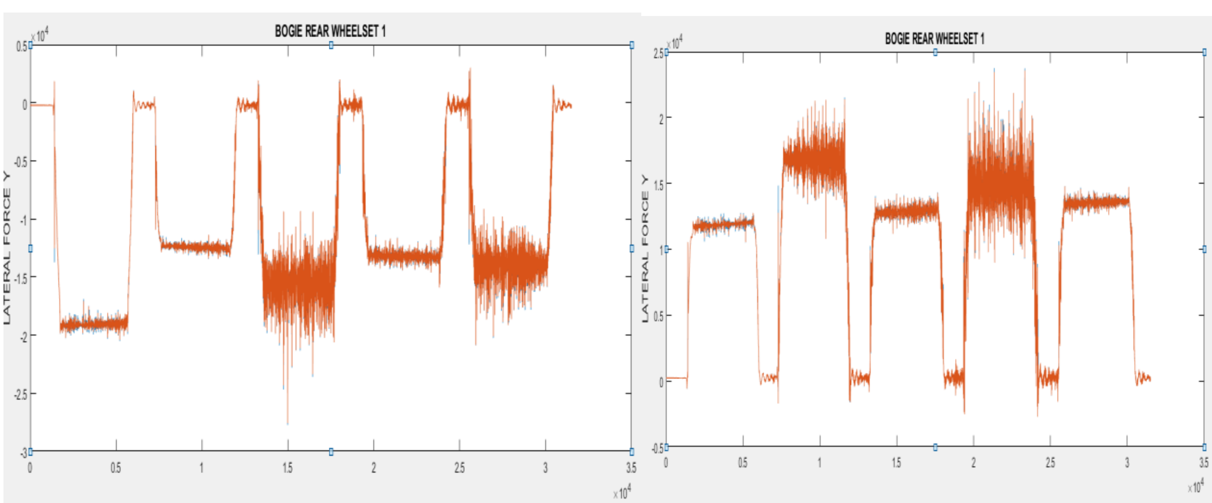


Fig.45 Lateral forces Y

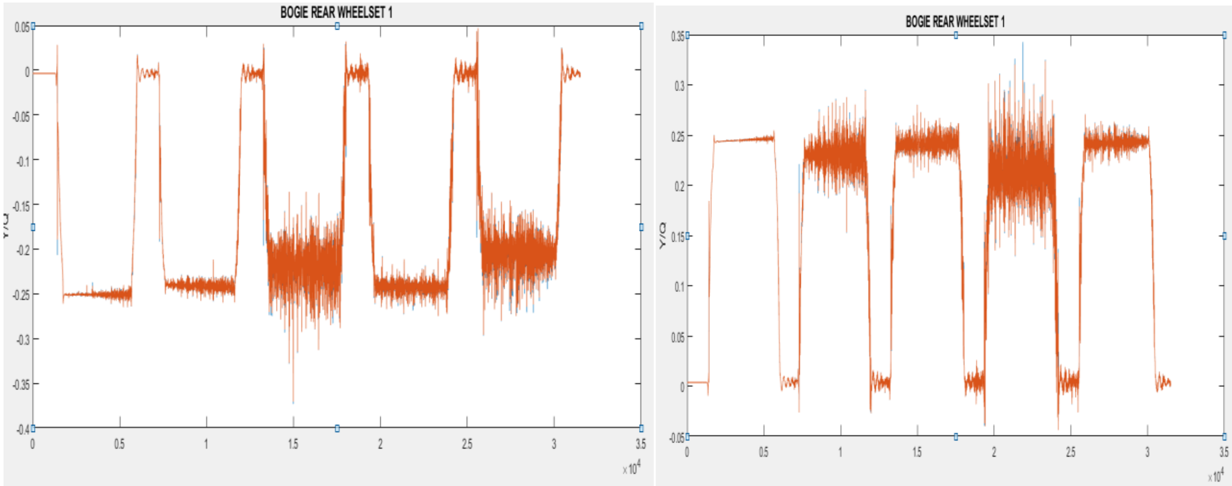


Fig.46 Quotient of lateral over vertical forces (Y/Q)

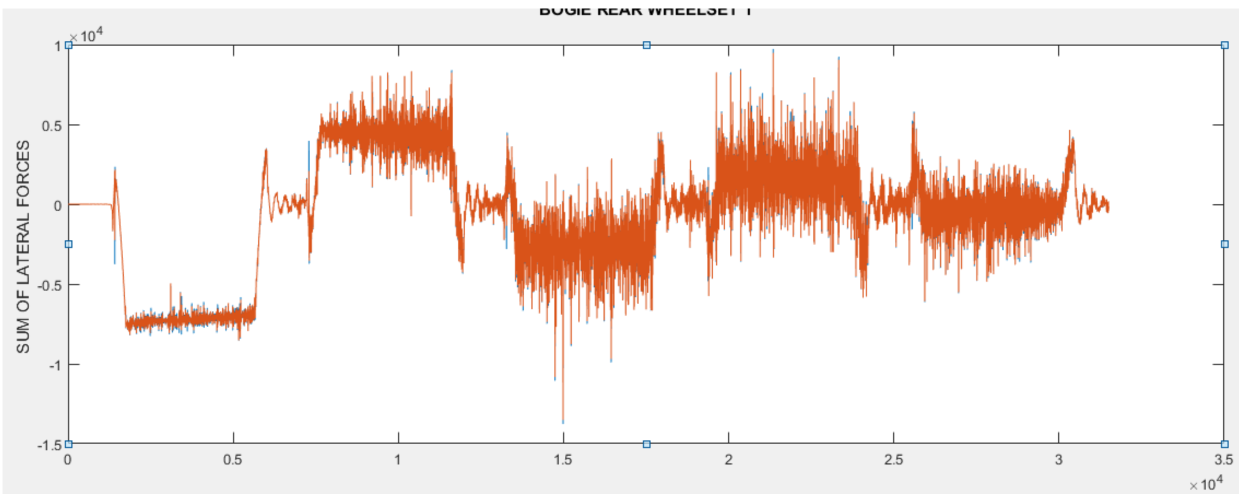


Fig.47 Sum of lateral forces

BOGIE REAR WHEELSET 2 :-

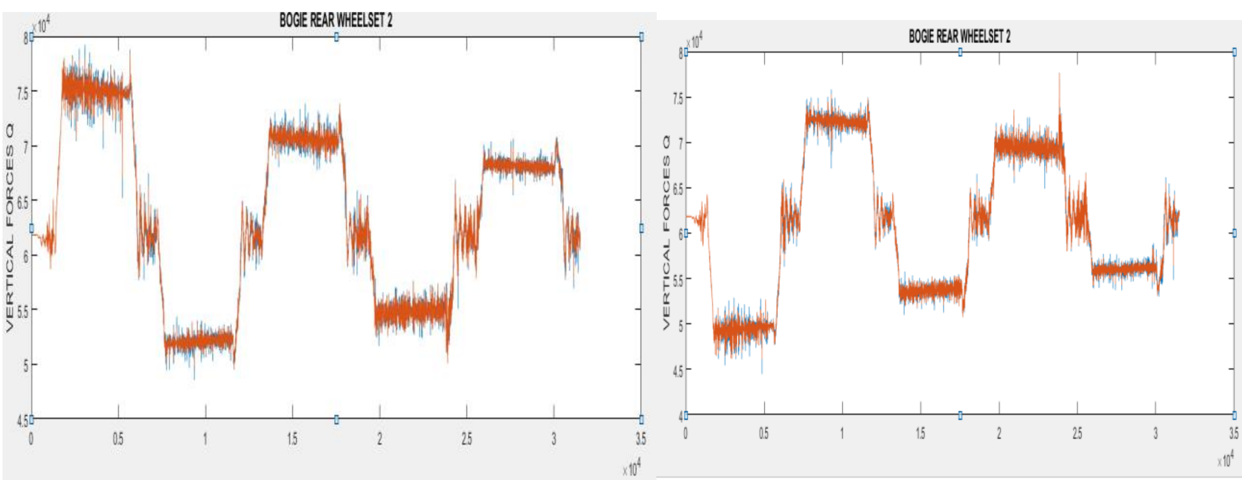


Fig.48 Vertical force Q

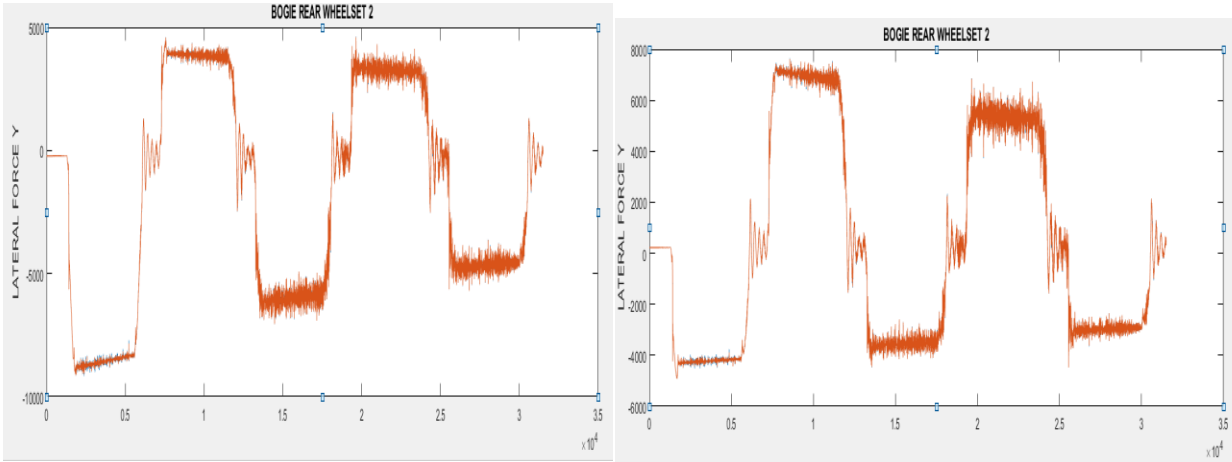


Fig.49 Lateral force Y

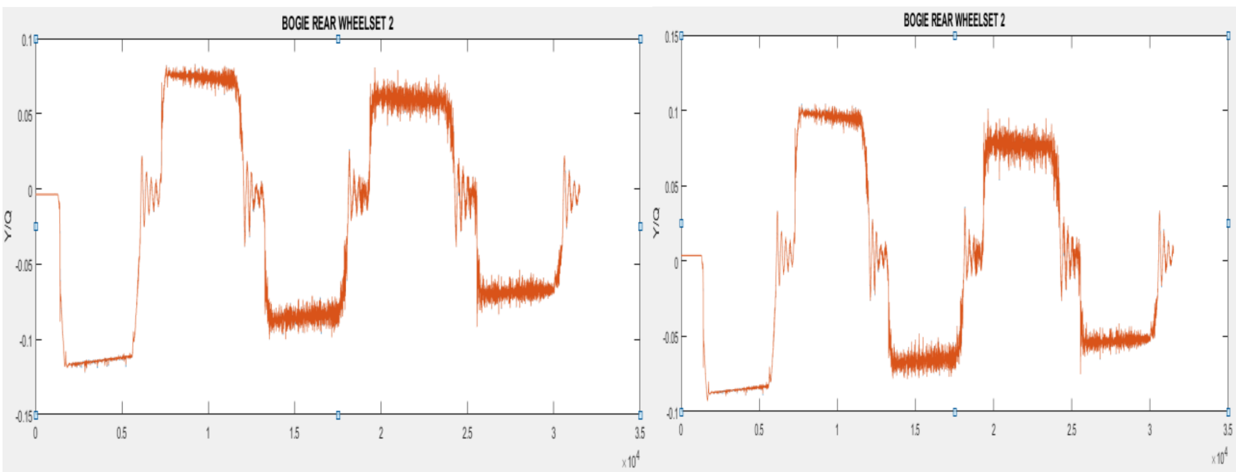


Fig.50 Quotient of lateral over vertical forces

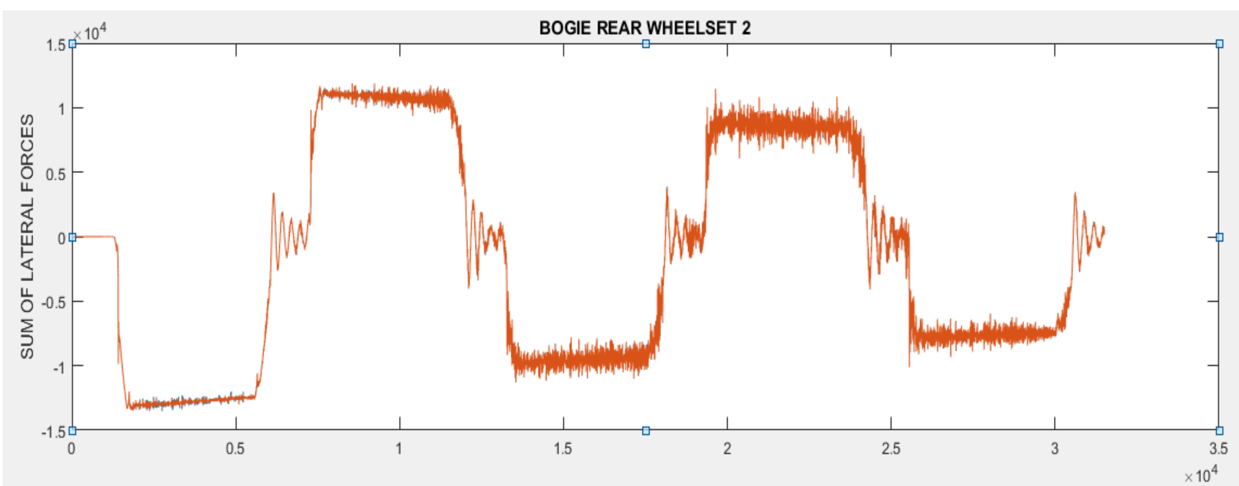


Fig.51 Sum of lateral forces

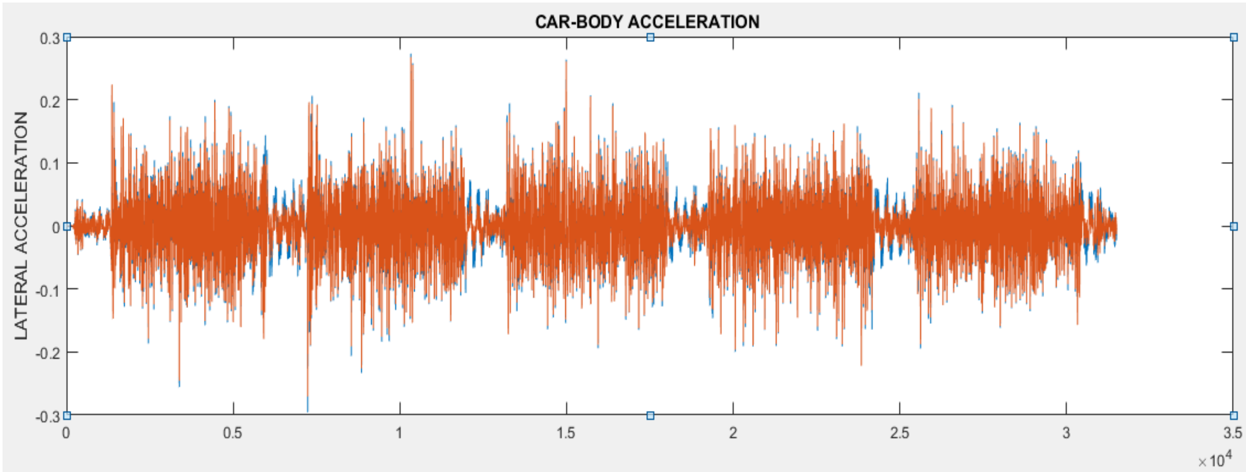


Fig.52 Lateral acceleration

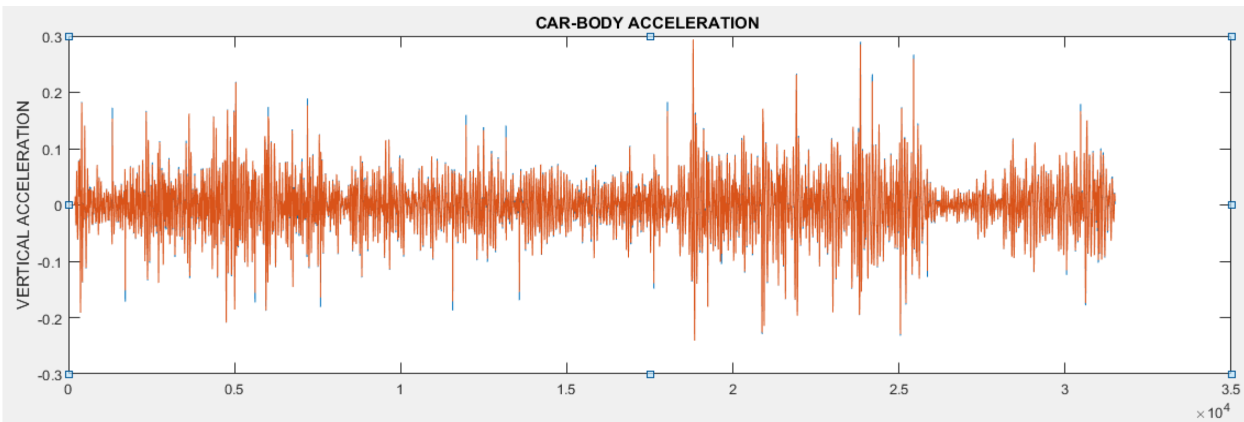


Fig.53 Vertical acceleration

Filtering Results on Test Zone 4 :-

BOGIE FRONT WHEELSET 1 :-

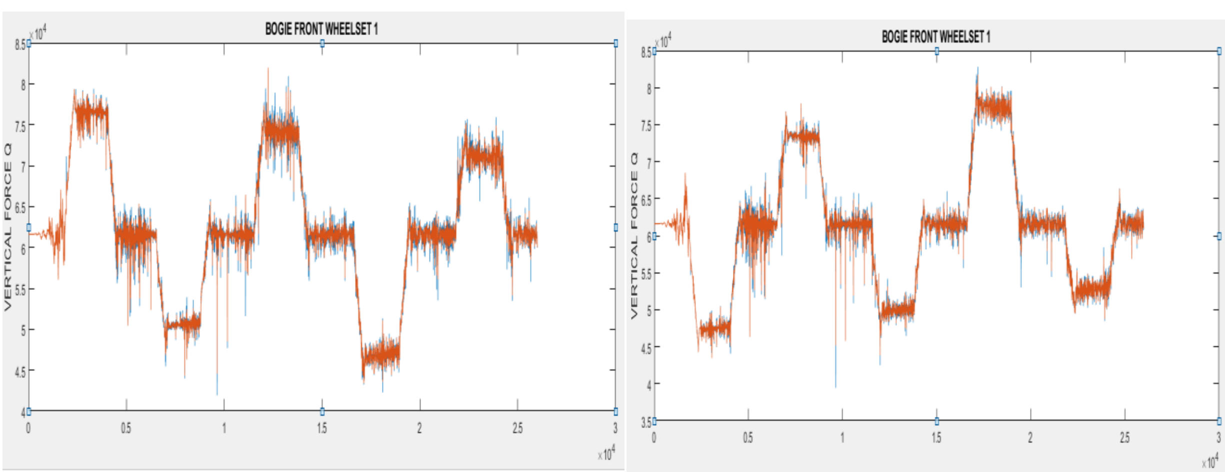


Fig.54 Vertical force Q

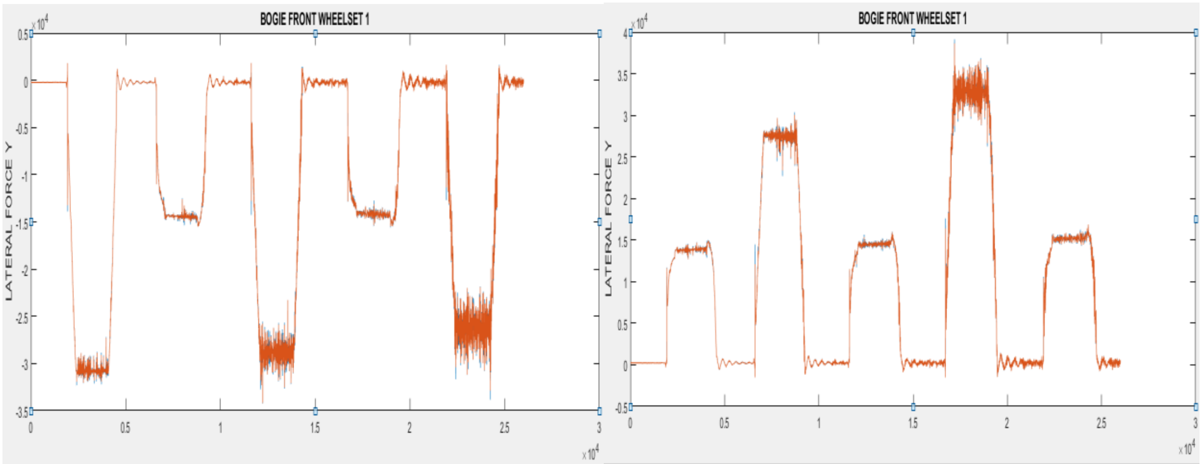


Fig.55 Lateral force Y

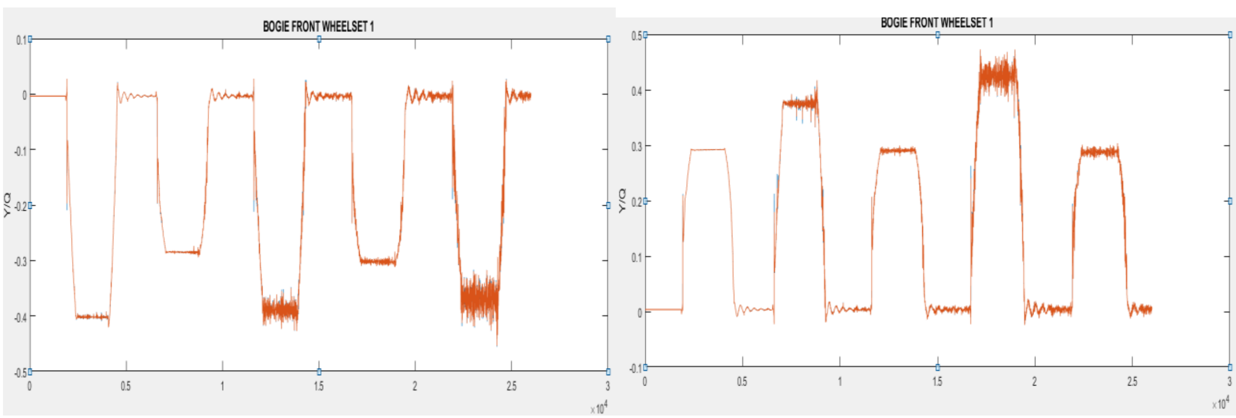


Fig.56 Quotient of lateral over vertical forces (Y/Q)

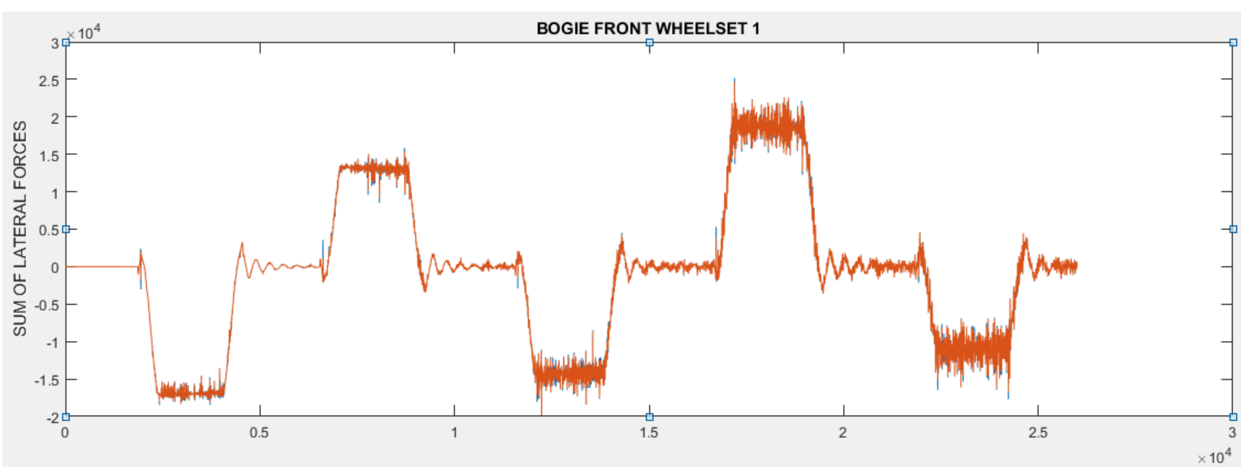


Fig.57 Sum of lateral forces

BOGIE FRONT WHEELSET 2 :-

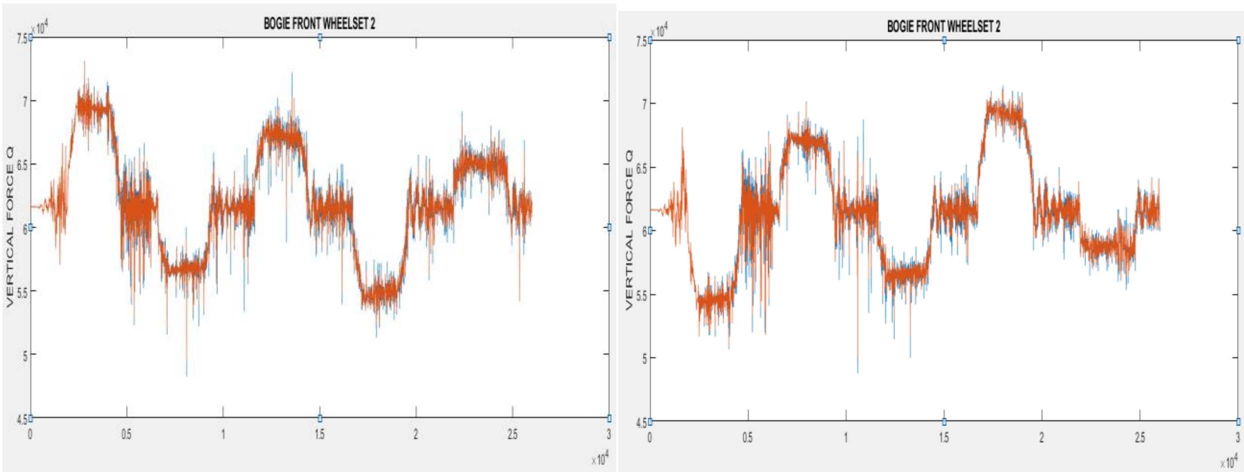


Fig.58 Vertical force Q

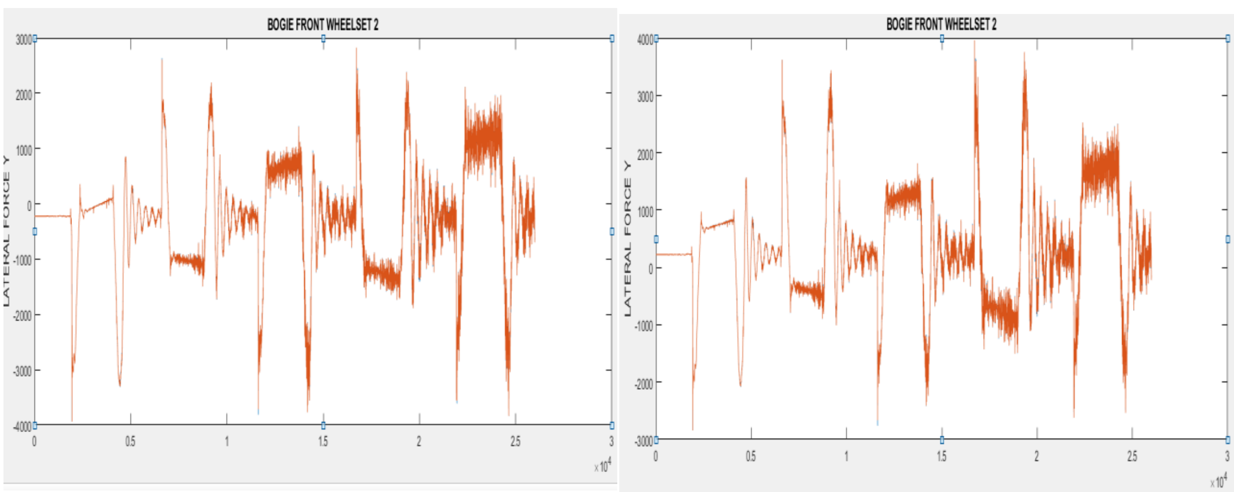


Fig.59 Lateral force Y

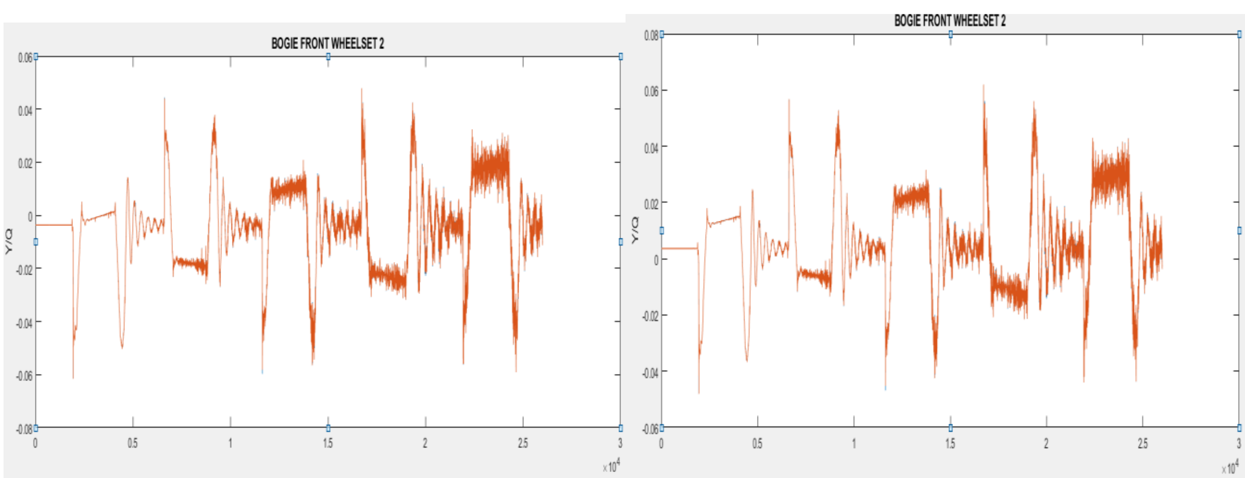


Fig.60 Quotient of lateral over vertical (Y/Q)

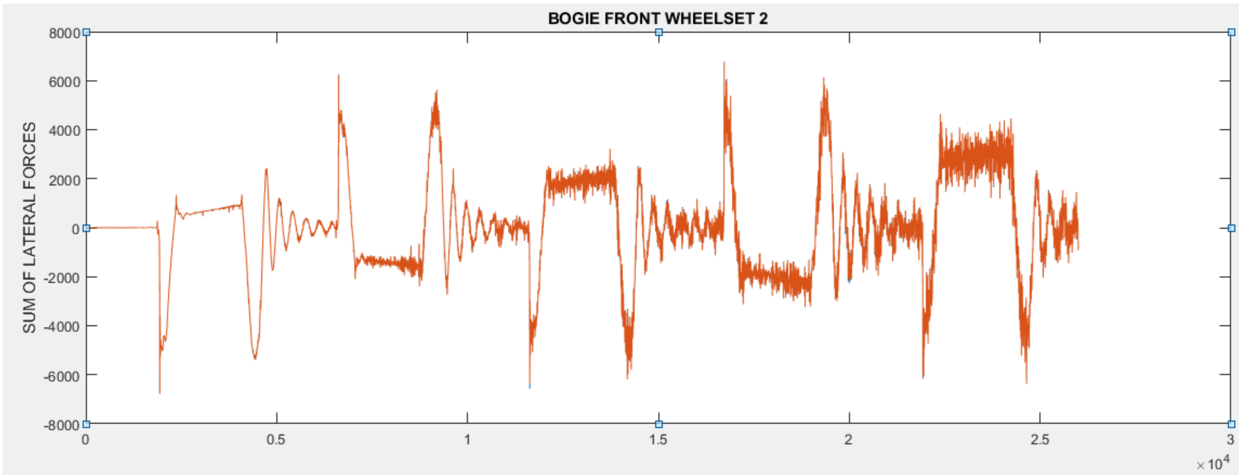


Fig.61 Sum of lateral forces

BOGIE REAR WHEELSET 1 :-

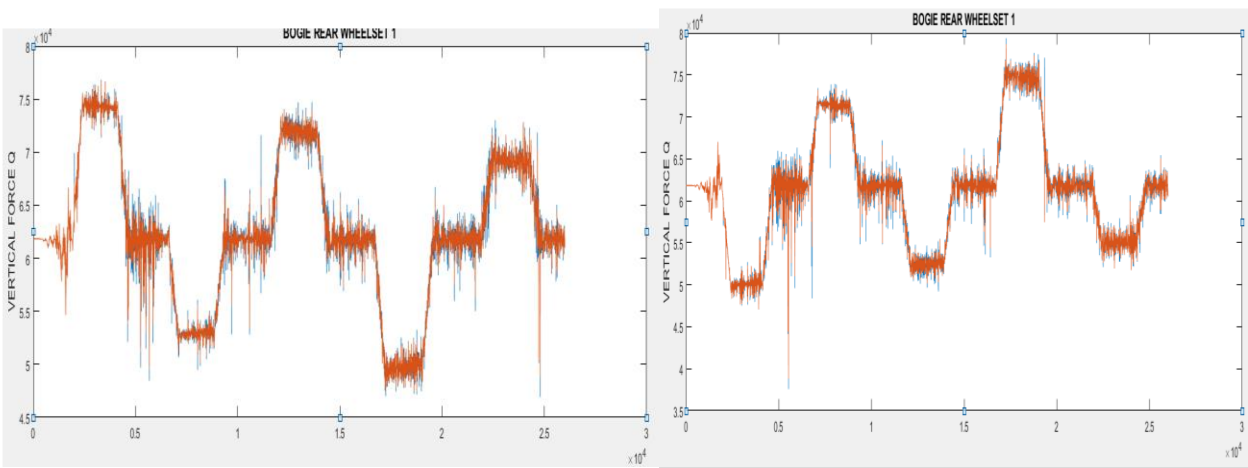


Fig.62 Vertical force Q

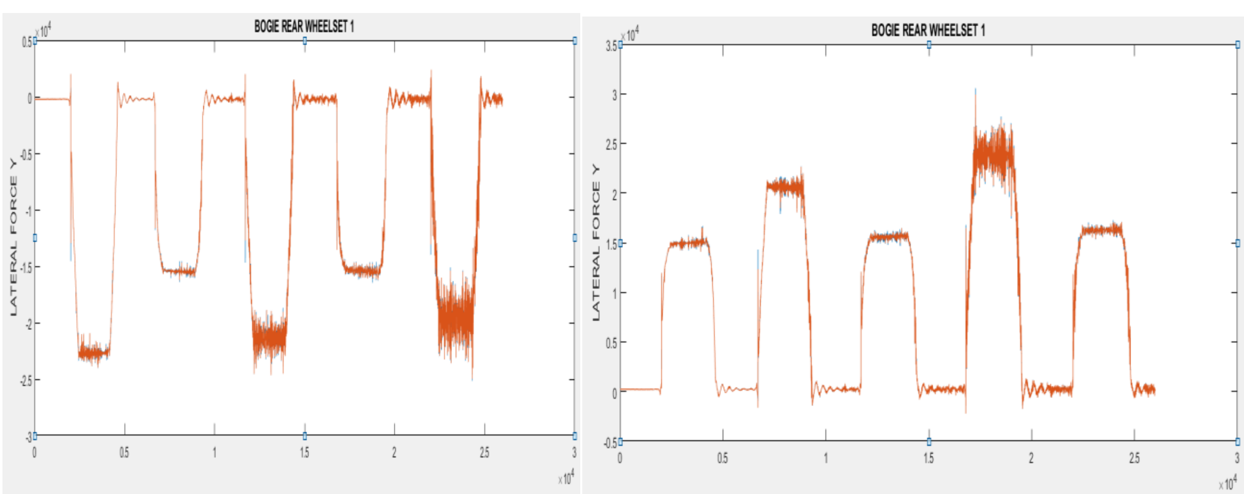


Fig.63 Lateral force Y

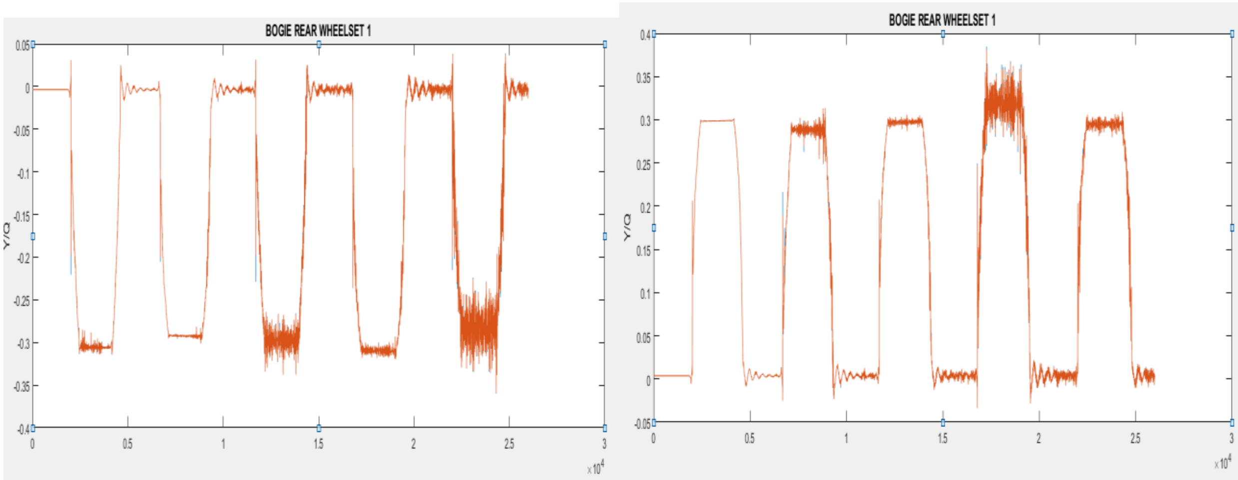


Fig.64 Quotient of lateral over vertical force (Y/Q)

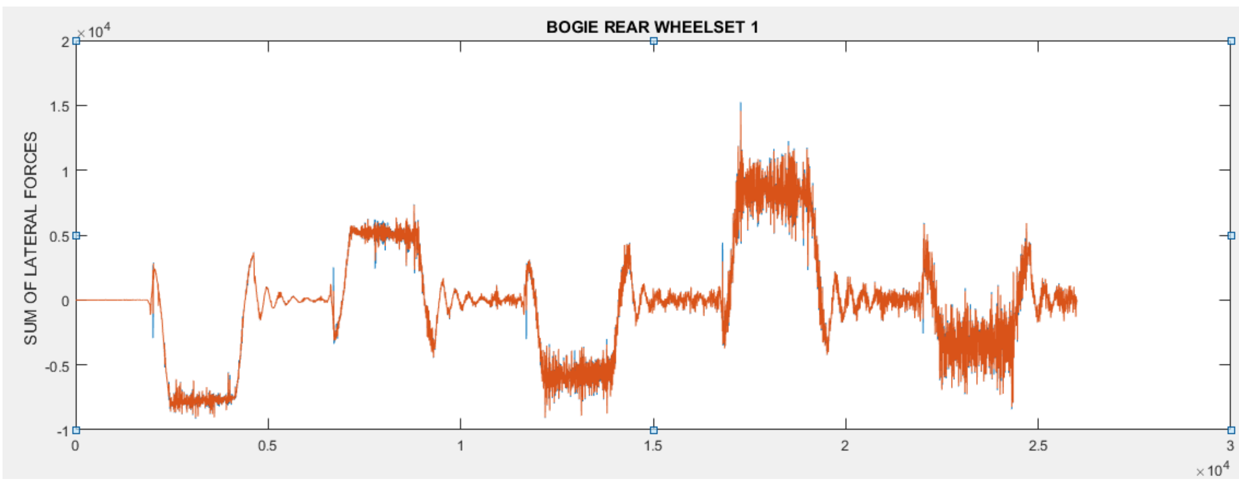


Fig.65 Sum of lateral forces

BOGIE REAR WHEELSET 2 :-

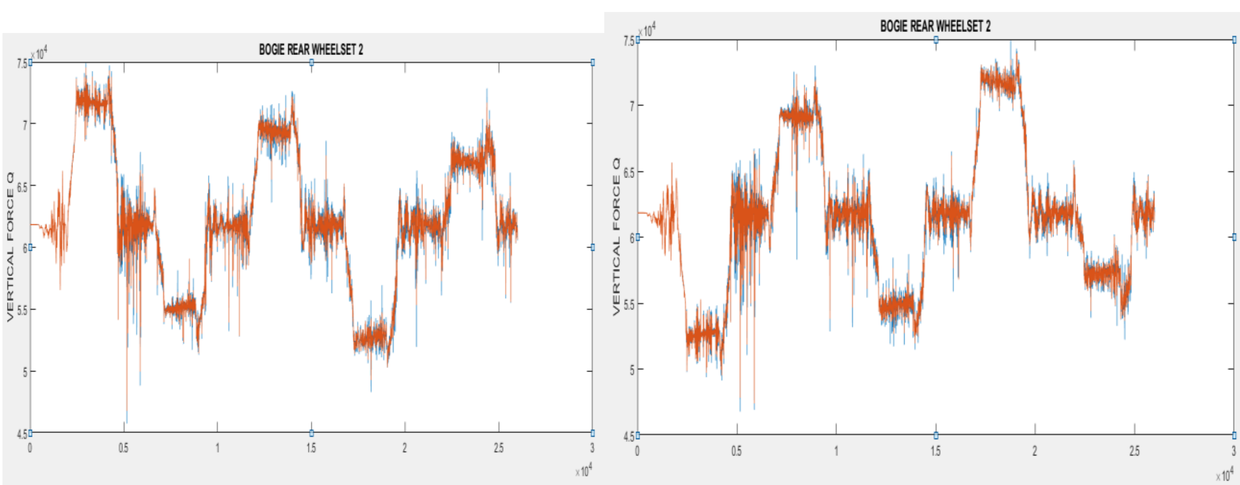


Fig.66 Vertical force Q

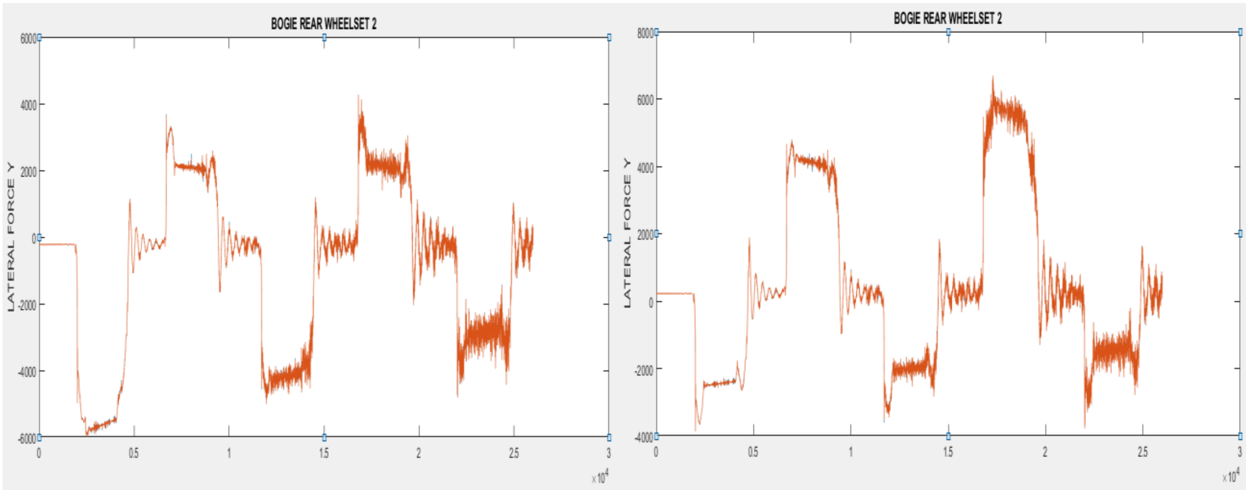


Fig.67 Lateral force Y

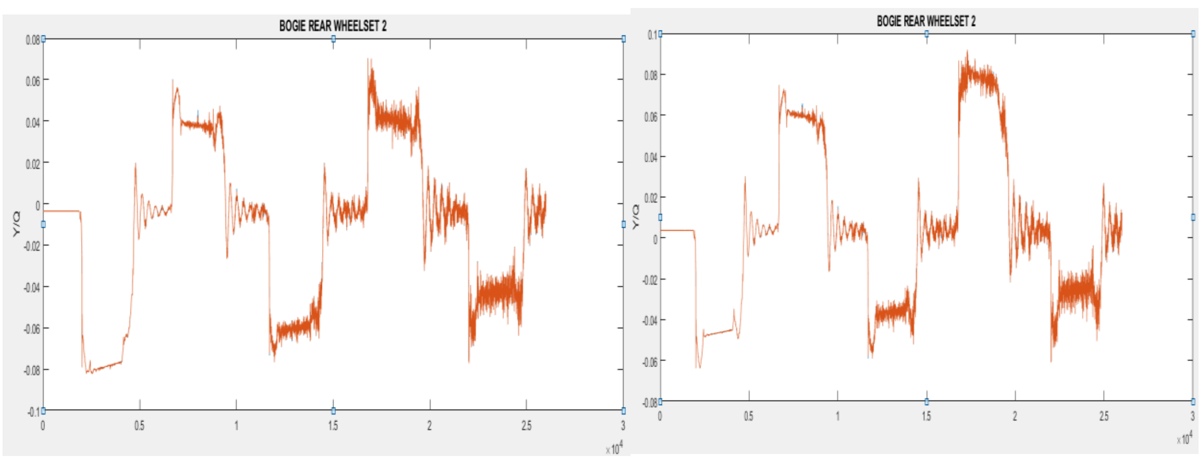


Fig.68 Quotient of lateral over vertical force (Y/Q)

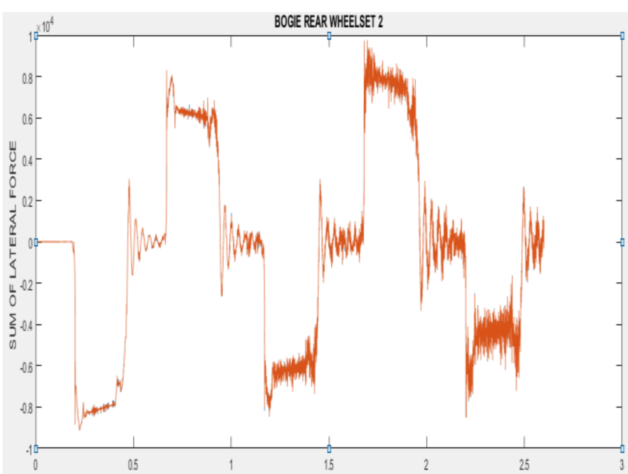


Fig.69 Sum of lateral forces

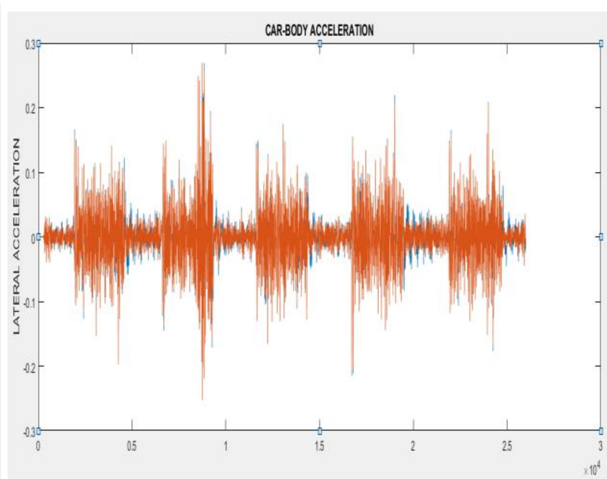


Fig.70 Lateral acceleration