CORRELATION OF LATERAL AND YAW ANALYSIS RESPONSES TO TRACKING OF LINEARLIZED RAIL WHEELSET MODEL

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ABSTRACT

Controlling analysis for lateral and yaw motion has great influence on rail wheelset model during running. To avoid slip due to lower adhesion, sliding due to higher speeds and balance of creep forces is attributed by degree of freedom (DOF). Here simple dynamics of lateral and yaw motions in terms of displacement, velocity and acceleration has been discussed. This correlation depending upon creep co-efficient is shaped into matrix form too. In this paper an effort has been consumed to observe the correlation and behavior of the lateral and yaw motion analysis based upon its geometry. The railway wheelset is modeled depending upon preliminary values of parameters. The step response of lateral and yaw motion has been performed to study attitude of each other based upon time variant.

KEYWORDS*: Creep co-efficient, Conicity, Forward velocity, Angular velocity, Degree of freedom*

1.0 INTRODUCTION

It has been observed that Mechanical systems need explanation of concerned elemental motion of bodies realizing their large movements, pertaining complicated interaction with their surrounding environment. The interaction for multi-body systems is conceived as multiple-body systems connected by different types of kinematic pairs, and forces acting upon it allow them to study the dynamic phenomena occurring in the during dynamic position (Polach, 2005). For correct modeling, all Eigen damping properties of rubber elements, as well as other parasitic damping have to be considered in the model parameters. The modes and nomenclature used for car body Eigen behavior are shown necessary (Lee, 2005). The sway mode, as combined lateral movement and rotation about longitudinal axis, is present in two forms with different heights of the rotation center lower sway mode and upper

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sway mode (Anant, 2004). The difference in the rolling radii of the two wheels is created when the wheelset is moved to one side due to curved path. Since the wheels are rigidly connected together by the solid axle. These wheels usually spin at the same rate. The forward velocity of the first wheel becomes larger than the forward velocity of the second wheel on diversion of path. This creates a rotation of the axle towards the center of the track position, with the angle of yaw. This continues to increase until the axle center goes back to the middle of the track position. The motion changes the solid axle oscillation from side to side accompanied by lateral and yaw motion referred as hunting during the running (Baldovin, 2012). The hunting motion caused by railway vehicles is combined by lateral and yaw self-oscillatory motion, which can largely be determined by wheel–rail contact geometry of rail wheelset.

The stability of this occurred motion is an important dynamic problem that solely depends upon the railway vehicles speed to determine the maximum operating speed of the rail vehicle (Yabuno, 2002). The Lateral movement of the wheelset creates the rolling radii difference that allows the wheelset to roll through the curve. As the curvature increases, the wheelset displaces more and generates a larger difference of the wheel radii, increasing the rate of yaw rotation. The yaw rotation rate, and hence the curvature that the wheelset can smoothly roll through, is limited by the maximum wheel radii difference. This, in turn, is limited by the clearance between the wheel flanges and the rail as the gauge clearance (Dukkipatti, 2002). The path curvature of rail wheelset cannot directly be measured, and lateral acceleration is due to disturbances created like body roll; also, the lateral acceleration depends upon sensor location, different to the yaw rate, which is only sensitive to sensor orientation installed (Snen et al. 2006). It is also important to note that due to simple conditions of constant speed, the minimal rail vehicle sideslip occurs when the vehicle is in a normal stable condition and due to the negligible roll angle of body, the three mentioned variables path curvature, yaw rate and lateral acceleration are actually proportional to each other on observation (Zelenka et al.2010)

In this paper, the behavior of lateral and yaw dynamics has huge influence upon the control and proper running of rail wheelset both on straight and curved track. These are fundamental motions based upon adhesion level and creep forces affecting braking system of railway vehicle system are also enumerated.

2.0 RAIL WHEELSET DYNAMICS

The fundamental dynamics railway wheelset model is here classified by two clauses. One pertains to geometry of wheelset model to prepare proper modeling and other relates to basic movement of the railway wheelset during running.

2.1 Mathematical Modeling

If track is considered to be rigid then the wheelset has three degrees of freedom, lateral displacement y, yaw movement Ψ, and longitudinal motions x, as shown in Figure 1. Lateral and yaw motion are very small as compare to longitudinal motion but play an important role in stability and ride comfort of the vehicle (Soomro, 2014)

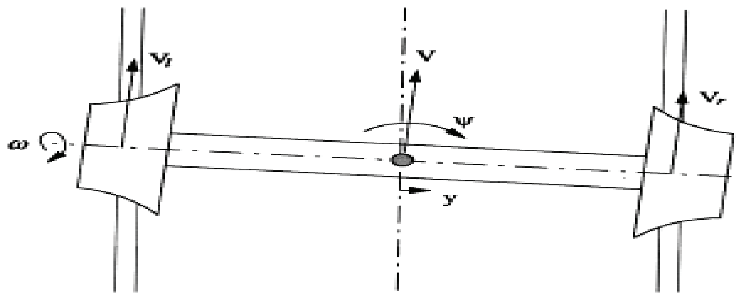

Figure 1. Rail wheelset geometry showing lateral and yaw motion

From Figure 1, we extract the relation as $V=\omega.r_o$, where $V_L=\omega.r_L$, $V_R=\omega.r_R$,

Thus $V=(V_L + V_R)/2 = \omega.r_o.$

The Constraints in lateral (y) and yaw (ψ) are $\dot{y} = v \sin \psi = v.\psi$, and $\psi = \dot{y}.v$, after rearranging we get $\dot{\psi} = (V_L + V_R)/2L_g = -(\omega.\Delta r)/2L_g$,

$$\dot{\psi} = -[V/(L_g.r_o)] * \lambda .y \tag{1}$$

Where $\lambda_y = \frac{\dot{y}}{v} - \psi$,

thus
$$\ddot{y} = \frac{2f_{22}}{m_w}\psi - \frac{2f_{22}}{m_w}\frac{\dot{y}}{v} \tag{2}$$

Where $f_{22} = F_y / \lambda_y$ and $f_{22} = F_x / \lambda_x$.

$$\ddot{\psi} = \frac{L_g f_{11} r_o \omega_R}{v I_w} - \frac{L_g f_{11} r_o \omega_L}{v I_w} - \frac{2L_g^2 f_{11}}{I_w}\frac{\dot{\psi}}{v} - \frac{2L_g \gamma f_{11}}{r_o I_w} y - \frac{2L_g \gamma f_{11}}{r_o I_w} y_t - \frac{k_w}{I_w}\psi \tag{3}$$

$$\frac{d}{dt}\begin{bmatrix} y \\ \psi \\ \dot{y} \\ \dot{\psi} \end{bmatrix} = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & \frac{2f_{22}}{m_w} & -\frac{2f_{22}}{v m_w} & 0 \\ -\frac{2L_g \gamma f_{11}}{r_o I_w} & -\frac{k_w}{I_w} & 0 & -\frac{2L_g^2 f_{11}}{v I_w} \end{bmatrix} \begin{bmatrix} y \\ \psi \\ \dot{y} \\ \dot{\psi} \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ \frac{2L_g \gamma f_{11}}{r_o I_w} \end{bmatrix} y_t \tag{4}$$

For a single wheelset, the second-order differential equations that represent the relationship of creep damping and creep stiffness coefficient with lateral and yaw displacement can been shown below considering the mass, lateral force and external yaw torque.

$$\ddot{y} = \frac{-2f_{11}}{mV}\dot{y} + \frac{-2f_{22}}{m}\psi + \frac{1}{m}F_y \tag{5}$$

$$\ddot{\psi} = \frac{-2f_{11} l\lambda}{I_w r} y - \frac{-2f_{11} l^2}{I_w V}\dot{\psi} + \frac{1}{I_w}T_w \tag{6}$$

These mathematical wheelset model parameters will be used for simulating results through Table 1 values to observe behavior of lateral and yaw motions (Soomro, 2015).

2.2 Degree of Freedom Railway Model

The Figure 2, shows the possible movements of railway vehicle with respect to 'X' in Horizontal plane and 'Y' both in lateral and yawing motions. While rolling wrt 'Y' Horizontal plane and 'Z' in Vertical plane and bouncing and pitching occur in 'Z' Vertical plane and 'X' horizontal planes. The railway wheelset has basic three degree of freedom (longitudinal, lateral and yawing), but here in Figure 2, six possible DOF are shown which are related with eachother.

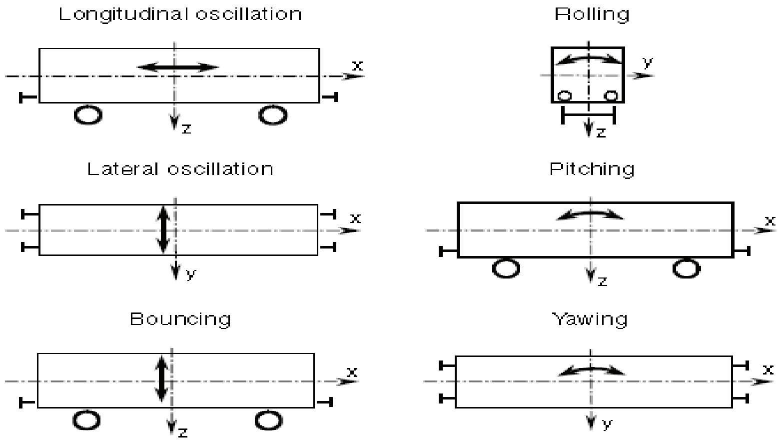

Figure 2. Possible Types of motions created by rail vehicle during running

2.3 Proposed Linearized Modelling

A schematic idea for having simplified model is invented as under.

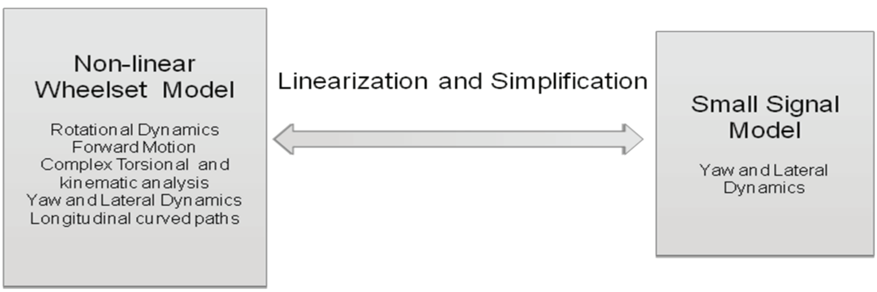

Figure 3 . Schematic Diagram from non-linear to linear modeling

Here in Figure 3, non-linear model railway wheel set model is linearized and simplified to limit it up to lateral and yaw motion analysis. As these are easily calculated and computed to check the behavior of railway locomotive lateral and yaw motion analysis through running.

Table 1 preliminary parameters with values used for modeling

Parameter	**Value**
Mass of Vehicle (M_v)	15000 Kg
Right wheel moment of inertia (I_R)	133.2 Kgm^2
Left wheel moment of inertia (I_L)	62.8 Kgm^2
Wheels radius (r_o)	0.5 m
Torsional Stiffness (k_t)	6063260 N/m
Conicity of Wheel(γ)	0.15
Mass of Wheelset (m_w)	1250kg
Curve Radius (R_o)	100m

The different parameters used in the modeling of simplified rail wheelset are enumerated in above Table 1. The values of different parameters are mentioned. These values are used by Matlab code and Simulink blocks to study behavior of lateral and yaw analysis. Thus the correlation between these dynamical terms is sketched by concerned graphical diagrams.

3.0 GRAPHIC SIMULATION RESULTS

The lateral and yaw motions created due to running of rail wheelset locomotive are numerated by Matlab simulation. Following are the various simulation results denoting the correlation of lateral and yaw dynamics. The values mentioned in Table 1 are used. In above Figure 4, the lateral and yaw displacements have been shown in vertical plane and time in horizontal plane. The black '+' curve shows lateral distance while blue diamond line shows the yaw distance. Here lateral curve shows behavior in zigzag making like triangle by points on 3, 6 and 7 on vertical plane inclined within time periods 0.4, 0.7 and 1 sec. Whereas yaw line is marked 1, 3, 5 and 8 in 0.1, 0.4, 0.7 and 1 sec with horizontal. This conceives the concept that when yaw reaches in 0.1 to 1 sec in horizontal to 8cm, the lateral displaces upward direction in 0.4, 0.7 and 1 sec to complete 7cm, yaw goes upward and laterally in triangular direction. From this graph, it can be assumed that both lateral and yaw are proportional with each in different directions on running rail wheelset. The lateral and yaw distances are usually smaller during the running of railway train to increase in minor steps within span of time. From below graph it is observed, that yaw distance is greater than lateral within same time.

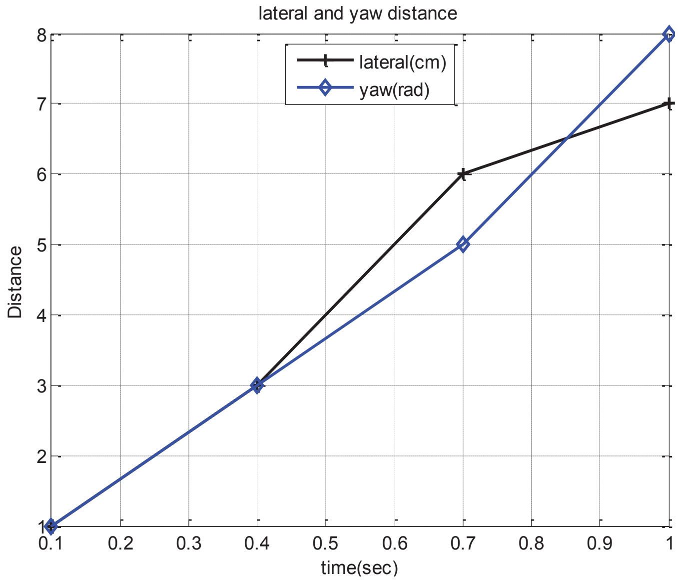

Figure 4 Relation of lateral and yaw displacement of rail wheelset

In Figure 5 below, the relation between lateral velocity and yaw velocity has been shown in vertical plane with respect to time in horizontal plane. The black '+' curve shows lateral velocity while blue diamond line shows the yaw velocity. Here lateral curve shows behavior in zigzag making like triangle by points from 0 0n 0.1 sec to reach upward 4000 on 0.4 sec then declines below 0 on 0.7 sec and end up to zero in 1 sec on horizontal plane. Whereas yaw line is marked below -1000 on 0.1 to -3000 in 0.4 sec and upwards to 0 in 0.7 sec with horizontal plane and ends below 0 on -200 rad/sec in 1.0 second on horizontal side. This conceives the concept that yaw velocity varies differently to the lateral velocity on 4000 cm/sec in upward direction in 04 seconds. Yaw goes upward to zero with a little bit downfall of lateral velocity on -200 cm/sec in 0.7 seconds. Thus lateral velocity ends at zero in one second. From this graph, it can be assumed that both lateral and yaw are initially more inversely proportional with each in different directions and after 0.7 second its inverse proportion decreases to end after one second. The lateral and yaw velocities are expressed in 'cm/sec' and 'rad/sec' respectively.

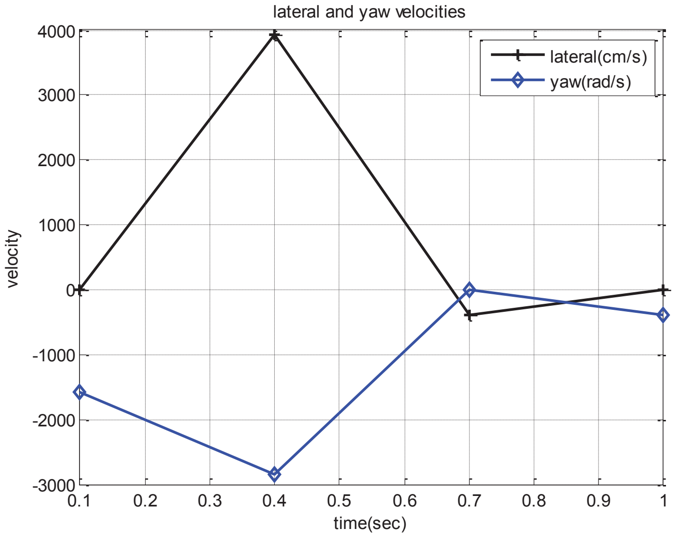

Figure 5. Lateral and yaw velocity behavior with each other on running wheelset

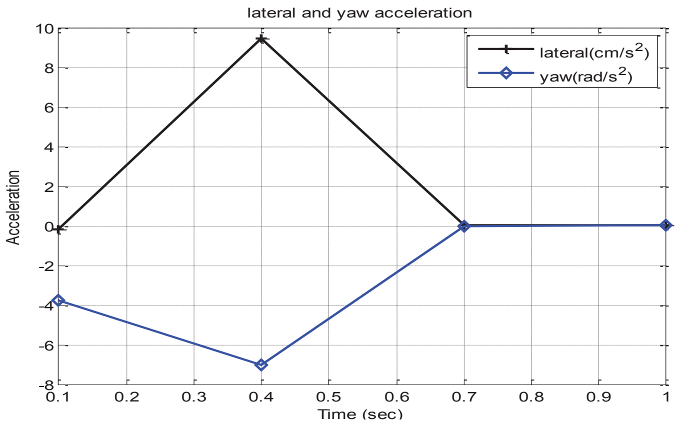

Figure 6. Acceleration of lateral and yaw of rail wheelset

In Figure 6, the relation between later acceleration denoted by black '+' curve and yaw acceleration by 'blue diamond' are shown. Here lateral acceleration starts from 0 on 0.1 sec hyperabolly upto nearby below 10 0n 0.4 sec and ends on zero on 0.7 sec to 1 sec in straight line. While yaw blue line starts from -4 0n 0.1 sec to 0.4 sec on below -6 on vertical plane and jumps upto 0 on 0.7 sec and ends on 1 sec in straight line. From this it can be assesed that these acceleration curves initialy behave inversely and then both end to go in straight line on zero from 0.7 sec to 1 sec. This displays unstability, where both lateral and yaw do not oppose each other. The lateral acceleration is expressed in terms of 'cm/sec2' and yaw or spin acceleration is denoted by 'rad/sec2' as displayed in

Figure 6. The below Figure 7, has been extracted by simulink block diagram. In this Figure 7, step response has been shown for lateral motion in vertical direction to time in horizontal plane. Here lateral curve starts initialy and slighly in straight line to jump up parabolicaly 2e-3 m/s (20 cm/s) on vertical scale in 1 sec. Then it goes downward to below zero on -0.6e-3 m/sec in 2 sec and then travels to zero path in 3 sec to end in 10 sec. This shows again unstability of lateral motion in straight line. Thus acceleration expressed in 'cm/sec2' is represented by lateral parameter, whereas yaw shows as deceleration in opposite direction. These both then travel in straight path on increase of speed and span of time.

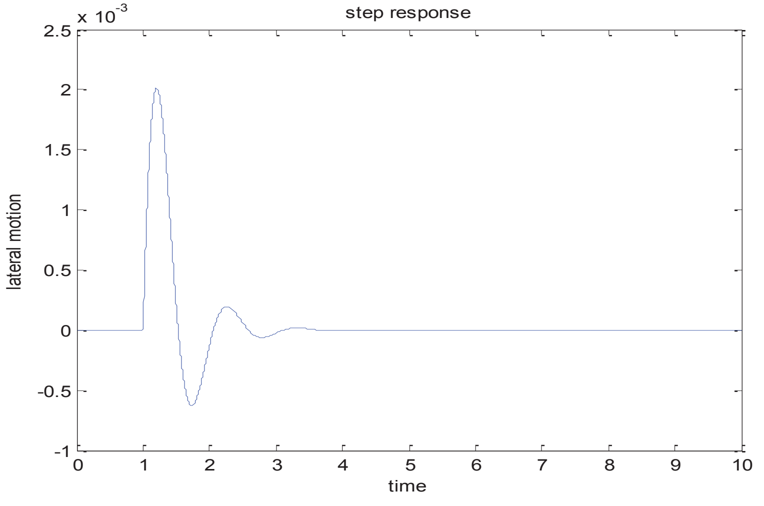

Figure 7. Step response of lateral motion of rail vehicle wheelset

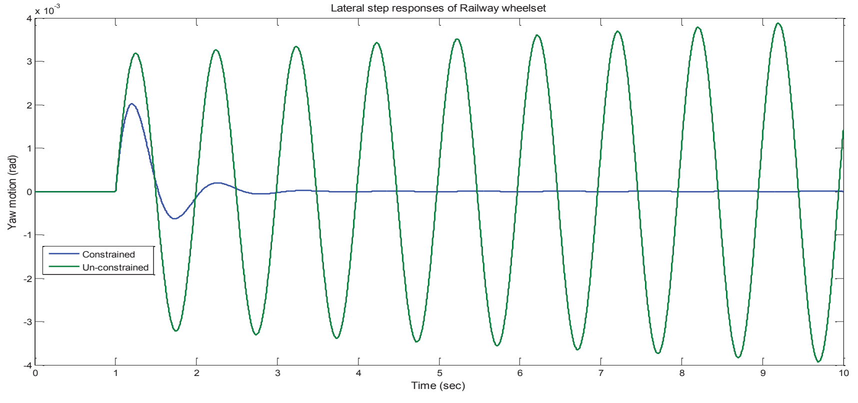

Figure 8. Constrained and unconstrained yaw motion of rail locomototive

Figure 8 above, shows the yaw motion of rail wheelset by simulink through step response. Here yaw motion is displayed both by unconstrained mode by green lines in zigzag form and constrained by blue line. The constrained mode starts initialy wih slight parabolicaly upto two steps of green line in same paths lower than green curve. Thus both go in straight path to end in 10 seconds. The unconstrained parameter moves in the range of the 3e-3 to -3e-3 radians. While the constrained line moves upward 2e-3 to -1e-3 radians in range, which shows its stability better that of unconstrained parameter for yaw motion in vertical direction.

4.0 CONCLUSIONS

From above analysis it is concluded that rail wheelset model is linearlised and simplified to the dynamics of lateral and yaw motion analysis related to longitudinal and later creep of co-efficient, skipping other affecting factors application to railway wheelset model. A suitable Matlab code has been created to observe the behavior of lateral motion analysis to yaw motion analysis through curves with each other. A Simulink block program has also been established to study step response of lateral and yaw motions separately. From the modeling the dynamics of lateral and yaw motions, it is accessed that both lateral and yaw vary in zigzag making triangles whereas yaw displacement starts initially horizontally. While velocity analysis of both lateral and yaw for wheelset vary inversely with each other. This inverse variation minimizes after some time before end. The acceleration analysis starts with same behavior and after some this inverse proportion is ended to travel in same path overlapping each other. In Simulink the individual behavior of both lateral motion and yaw with constrained and unconstrained is displayed. From this whole phenomenon it can be conceived that lateral motion and yaw behavior verses in opposite directions in velocities and at last in acceleration analysis.

NONMENCLATURE

y is lateral displacement of wheelset
ψ is yaw angle (angle of attack)
F_y is lateral force
T_ψ is yaw torque
m_w is mass of wheelset
I_w is moment of inertia for wheelset
f_{11} is longitudinal creep co efficient
f_{22} is lateral creep coefficient

REFERENCES

Polach, O. (2005). Influence of wheel/rail contact geometry on the behaviour of the railway vehicle at stability limit. *Enoc 2005, Eindhoven, Netherlands, 7*(12), 2203-2210.

Lee, S.Y., Cheng, Y.C. (2005). Hunting stability analysis of high-speed railway vehicle trucks on tangent tracks. *Journal of Sound and Vibration, 282,* 881-898.

Anant, M., Mehdi, A. (2004). Nonlinear investigation of the effect of primary suspension on the hunting stability of a rail wheelset. *ASME Rail Transportation Division, 27*, 53-61.

Baldovin D., Baldovin S. (2012). The lateral stability of a bogie with independently rotating wheelsets. *The Annual Simposium of the Inst. of Solid Mechanics*, SISOM.

Yabuno, H., Okamoto, T., Aoshima, N. (2002). Effect of lateral linear stiffness on nonlinear characteristics of hunting motion of a railway wheelset. *Meccanica, 37*, 555-568.

Dukkipatti, R.V., Narayana S, S. (2002). Lateral Stability and steady state curving performance of unconventional rail tracks. *JSME International Journal, Series C, 45*(1).

C Snen (2006). Railway applications testing for the acceptance of running characteristics of railway vehicles testing of running behavior and stationary tests (in Czech). *Czech Institute for Normalisation*.

Zelenka, J., Mich´alek, T. (2010). A new method of the assessment of rail vehicles guiding behavior in small-radius curves. International *Journal of Applied Mechanics and Engineering 15*(2), 511–519.

Soomro. ZA, I. Hussain, Chowdhary. BS, (2014). Creep forces analysis at wheel- rail contact patch to identify adhesion level to control slip on railway track. New Horizons, *Journal of IEEEP,* 14-17.

Soomro. ZA, (2015). Step response and Estimation of lateral and yaw motion disturbance of rail wheel set. *Journal of Engineering and Technology 5*(1), 1-8