



Dual estimation of lateral analysis for railway vehicle wheelset to control disturbance for smooth running

Zulfiqar Ali Soomro^{1,*}

¹Mech; Engg; Deptt; Quaid-e-Awam University of engg; Sc & Tech; Nawabshah. Pakistan.

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*Corresponding author: zulfiqarali_s@yahoo.com

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Abstract: The lateral aspects of railway vehicle wheelset have a significant impact on railway wheelset dynamic systems. Lateral analysis usually causes wheelset slippage from the track resulting insufficient adhesion which can lead to creep. Significant disturbances are mostly caused in lateral direction due to speed. This paper uses the dual Kalman filter strategy to deal with noise issues and thus minimizes the error ratio during observation. A single Kalman filter reduces errors to a minimum extent while the second estimator decreases the maximum available chance of error. Using a third estimator provides no further improvement over the dual Kalman filter implementation.

Keywords: Kalman filter, tractive effort, creep coefficient, yaw motion, hunting, adhesion, fuzzy inference system

Introduction

Unsafe wheel loading or lateral force can be compensated by reducing track irregularities. However very large wheel loads or lateral forces are caused by such short wavelength track irregularities which cannot be detected by track inspection cars. Moreover these large wheel loads or lateral forces are more likely to occur at higher speeds. Hence, high speed train operations require enhanced track maintenance [1,2]. In addition, different vehicle types will incur different wheel loads or lateral forces from irregularities on a single track, making it important to accurately identify actual wheel loads and lateral forces generated by vehicles even at such a short wavelength [3,4].

The lateral wheelset displacement of high speed railway vehicles can cause vibrations with large domain that define vehicle lateral instability in a phenomenon called hunting. Bifurcation analysis is commonly used to describe stability. To ensure vehicle safety and minimize track component deterioration, estimating wheel load and lateral force requires the identification of values that deviate from prescribed thresholds and the locations of these various values [5,6].

Current anti-slip protection/control schemes focus

on assessing wheel slip or slide and can be used to address the problem only after a wheel slip has occurred. There are no preventative measures that could stop wheel spinning (or brake locking). Keeping tractive effort below the adhesion level on the track would require reliable and real-time information of contact conditions [7,8]. The present study develops a practical method for real-time estimation of the wheel-track contact condition/adhesion. A previous study attempted to filter the creep coefficient at different rail-wheel contacts and their results are used here as an indirect indicator of adhesion [9,10].

Contact mechanics are highly non-linear in nature and are subject to large variations due to condition changes at point of contact between wheel and rail. The use of a single estimator, based on a linear (or linearized) model will have difficulty covering all possible operating conditions and account for all uncertainties [11,12]. This study designs a set of Kalman filters based on models linearized at different operating points on a creep curve, each of which is tuned to provide the best estimation for its specific conditions [13,14].

The rotational and longitudinal dynamics of a wheelset were considered and the effect of the interface condition on relevant zones is carefully estimated. Single Kalman filters are used to estimate the changes in



contact conditions based on torsional vibrations. Charles and Goodall estimated low adhesion between wheel and rail using vehicle responses to lateral track irregularities [15,16]. Multiple Kalman filters are used to estimate the states at different points of the creep curve. The proposed scheme offers a number of benefits that are not possible with the current direct measurement based detection/prediction techniques [9,10]. Different numbers of localized Kalman estimators can be implemented to filter the dynamic parameters in all possible operating conditions.

One of the proposed methods detects the wheel slip indirectly from the wheelset dynamic changes caused by wheelsets operating in unstable regions with non-linear contact characteristics as a consequence of wheel slip. The second method estimates the contact force saturation and identifies the maximum adhesion using a model-based technique that involves the use of multiple Kalman filters [17, 18].

In this paper the lateral rail-wheel dynamics are discussed and modeled mathematically. Simulations are performed in Matlab using a dual Kalman filter to estimate corresponding errors.

Rail-wheel dynamics in lateral mode

Variables for lateral analysis of railway dynamics include motion, speed and acceleration:

$$y = (V_L + V_R)/2L_g = -(\omega \cdot \Delta r)/2L_g \quad (1)$$

This describes the lateral motion consisting of the velocity of the right and left wheels, L_g = gauge length of wheel to axle, ω = angular speed, and Δr =difference of radius

$$\dot{y} = \frac{2f_{22}}{m_w} \psi - \frac{2f_{22}}{m_w \cdot v} \dot{y} \quad (2)$$

This describes lateral velocity, where m_w = vehicle mass, and v = vehicle velocity

$$\ddot{y} = \frac{2f_{22}}{m_w} \ddot{\psi} - \frac{2f_{22}}{m_w \cdot v} \ddot{y} \quad (3)$$

This describes lateral acceleration, where $f_{22} = F_y / \lambda_y$, lateral creep coefficient, $\psi = -\left[\frac{V}{(L_g \cdot r_o)}\right] \times \lambda_y$ (4)

This describes yaw motion, where $\lambda_y = \frac{\dot{y}}{v} - \psi$ is lateral creepage $\dot{\psi} = -\left[\frac{V}{(L_g \cdot r_o)}\right] \times \lambda_y/t$ (5)

This describes yaw velocity

$$\frac{d}{dt} \begin{bmatrix} y \\ \dot{y} \\ \ddot{y} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \frac{2f_{22}}{m_w} \psi - \frac{2f_{22}}{m_w \cdot v} & 0 \\ \frac{2f_{22}}{m_w} \dot{\psi} - \frac{2f_{22}}{m_w \cdot v} & 0 & 0 \end{bmatrix} \begin{bmatrix} y \\ \dot{y} \\ \ddot{y} \end{bmatrix} \quad (6)$$

These are the state space equations in matrix form.

Simulated Results

Figure 1 shows the railway wheelset lateral analysis in terms of motion, velocity and acceleration. Input sensors are used to measure the disturbance impact on the railway wheelset model in terms of lateral motion, speed and acceleration through three individual Kalman filters. The resulting residual generation provides outputs in the form of error identification for each lateral parameter according to the three estimators.

Simulations results are classified according to three lateral aspects derived using the three different estimators. The three estimators are shown in blue while errors are shown in green in subsequent sections.

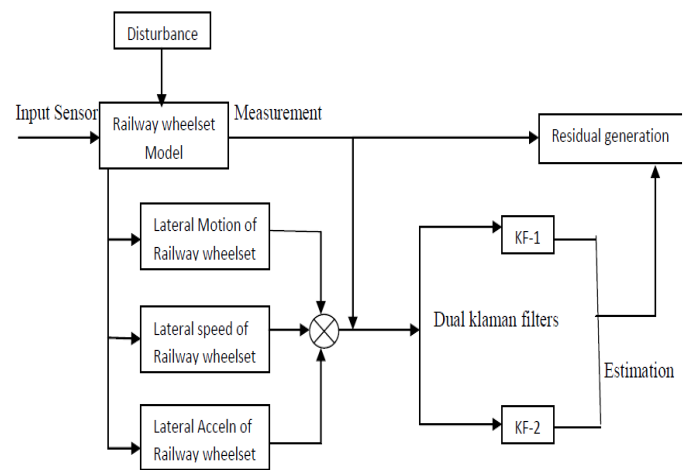


Figure 1. Block diagram for wheelset lateral analysis.

Lateral motion estimation

In Fig. 2, the disturbance for lateral motion is estimated using estimator-1 of the Kalman filter. The estimated signals overlap the error present in the running system. The error ratio exceeds the estimated values only at the signal peaks. The lateral motion varies from -0.023 mm to 0.02 mm within total duration of 10 seconds. Errors are found to be more abundant in the

Dr. Zulfiqar Ali Soomro is currently working as Associate Professor in the department of Mechanical Engineering at Quaid-e-Awam University of Engineering Science and Technology Nawabshah (Sindh) Pakistan. He received his B.E (Automobiles) from Mehran University, M.S (Robotics) from NUST Rawalpindi, PgD (Mechatronics) from AIT Thailand and PhD in Railway vehicle Dynamics from MUET. His research interests include Robotics, Mechatronics, and Railway vehicle dynamics and modelling. He has 26 years of academic and research experience. He has more than 26 international publications at journals of repute both in local and abroad journals. E-mail:zulfiqarali_s@yahoo.com

middle than that of estimated signals at corners.

As shown in Fig. 3, when the second filter is applied to overcome the lateral motion disturbance, the error ratio is exceeded by the estimated signals in comparison to the estimator-1 used in the previous tuning (Fig-1). Here the estimated signals are scattered by peaks from -0.02 to 0.023 mm of lateral motion while the error is limited between -0.015 and 0.013 mm on the vertical scale within a total duration of 10 seconds.

This shows that this is the last stage, and no vacancies remain for applying additional estimators to further decrease the error ratio.

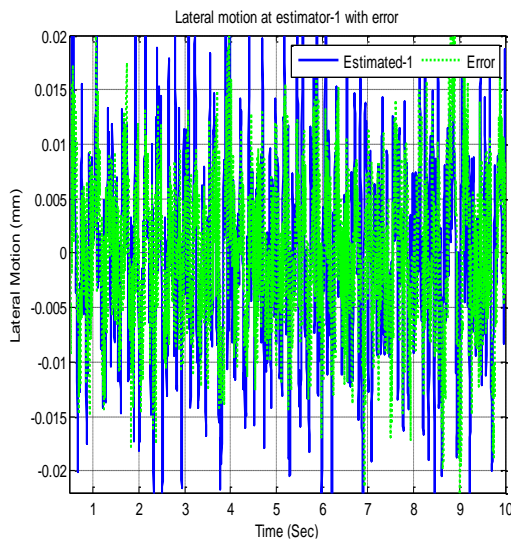


Figure 2. Lateral motion estimation by Kalman filter-1 with associated error.

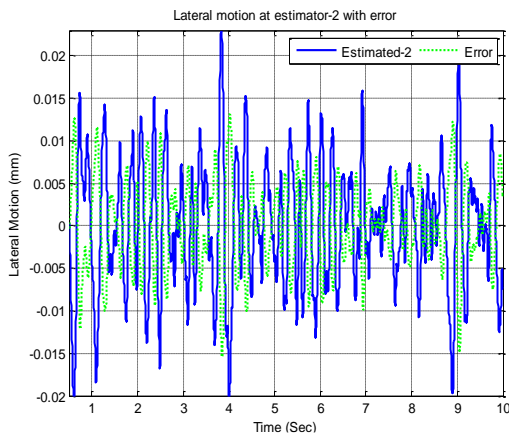


Figure 3. Lateral motion estimation by Kalman filter-2 with associated error.

Figure 4 shows the lateral velocity of the railway wheelset model, where signals achieved by estimator-1 scatter the minor error ratio.

Here the filtered lateral velocity value touches the borders from -0.32 to 0.35 mm/sec on the vertical plane over a 10 second duration. The error ratio is approximately 0 in terms of the lateral speed of the wheelset and then increases after 8 seconds with minor disturbances up to the 10 second limit.

In Fig. 5, error values are scattered among the estimated signals obtained by estimator-2 for the wheelset's lateral velocity. The error ratios peak from -2.6 to 2.8 mm/sec on the vertical axis, while the estimated signals are limited between -0.3 to 0.3 mm/sec during the prescribed 10 second duration. This shows that filtering lateral velocity by an additional estimator produces a large error ratio.

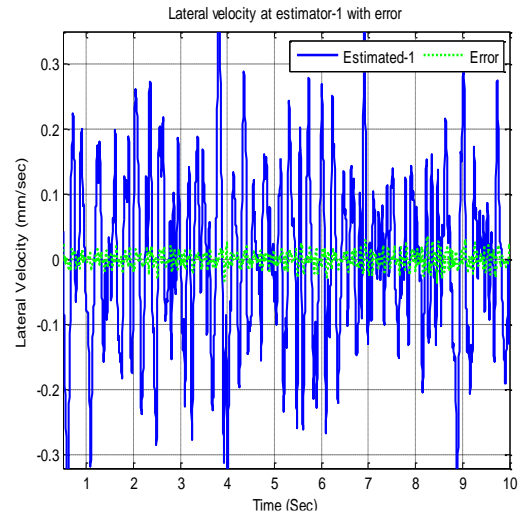


Figure 4. Lateral speed by Kalman estimator-1 with associated error.

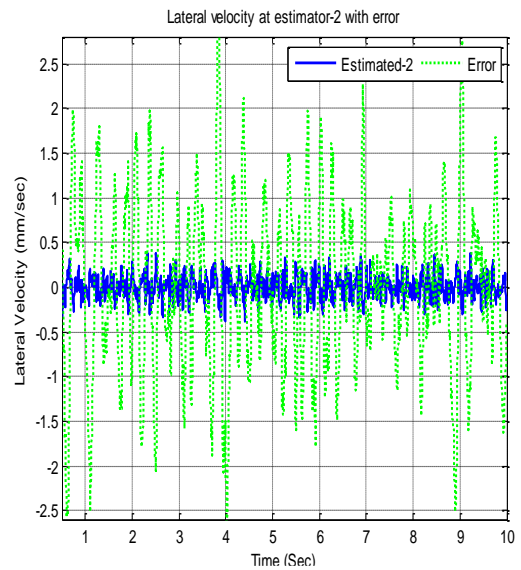


Figure 5. Lateral speed by kalman estimator-2 and procured error.

Lateral acceleration estimation

In Fig. 6, the lateral acceleration is filtered by Kalman filter-1, where the estimated signals are less abundant ranging from -0.01 to 0.01 mm/sec² on the vertical side of the lateral acceleration within the fixed 10 second duration. The error ratio abundantly ranges from -0.32 to 0.35 mm/sec² on the vertical scale of lateral acceleration [19].

In Fig. 7, the second Kalman estimator is used to filter noise during the lateral acceleration of a railway

wheelset against available errors. Here the estimated signals compete against the error values but peak heights for errors are only slightly higher than those of the estimated ratio in the range of -0.35 to 0.32 mm/sec².

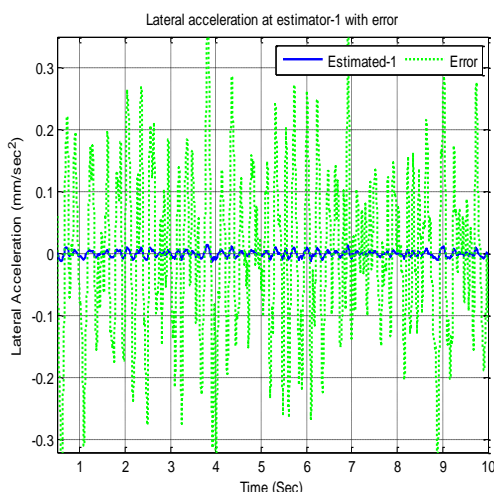


Figure 6. Lateral acceleration by Kalman filter-2 and associated error.

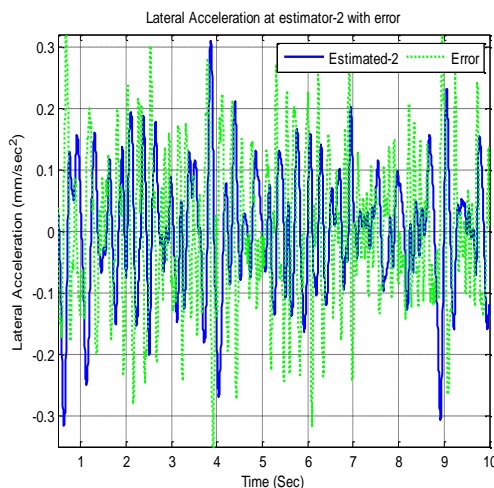


Figure 7. Lateral acceleration of wheels by Kalman filter-2 and associated error.

Fig-8 shows a 3D diagram of the lateral error values for the whole railway model system with their resulting segments. Lateral error-1 is scaled on the X-axis ranging from 0 to 1 in increments of 0.1 while the Y-plane displays lateral error-2 from 0 to 1 in increments of 0.2 at 0 of both X and planes through blue and yellow strips. The Z axis is shown as a vector of these two planes for segments ranging from 1 to -60, -40, -20 and 0. This surface diagram is drawn using fuzzy logic.

Conclusion

This paper discusses the lateral dynamics of railway vehicle wheelsets for mathematical modeling. The lateral analysis covers movement, velocity and acceleration due to the running position of the railway wheelset.

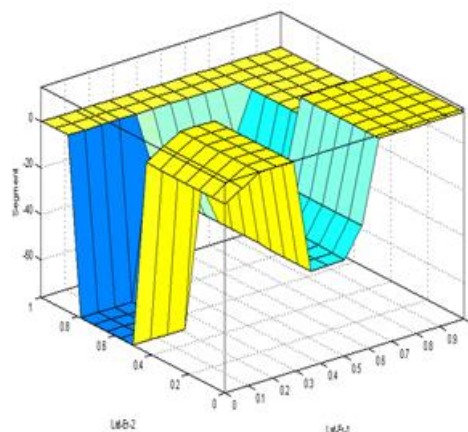


Figure 8. Surface 3D diagram by fuzzy inference for two lateral errors.

Simulations are run using the proposed model through Kalman filters to estimate signal disturbance with respect to actual (simulated) signals. Two Kalman filters are used to filter noise. One estimator measures the minimum error ratio while the second estimator computes the maximum error value caused by the generated noise.

Simulation results indicate that the lateral motion as estimated by Kalman filter-1 produces a higher error ratio that of estimated signals. But when estimator-2 is applied to check the result, the error ratio is lower than that measured by the estimated signal. The noise associated with lateral speed is totally different from that of lateral movement. When Kalman filter-1 is applied to lateral velocity, it yielded a much lower error ratio between -0.01 to 0.01 mm/sec. But using a second estimator produces markedly different behavior with a less dense estimated error ratio between -0.3 to 0.3 mm/sec with a higher error ratio. For lateral acceleration, the estimated signals wrap the zero axis with a thinner ratio covered by a very large error ratio. When Kalman filter-2 is applied, the condition changes to provide near parity between the estimated value and error ratio.

Hence it can be postulated that the error ratio is enhanced whenever the simple ratio of lateral motion is rated with respect to time to become the lateral velocity. When this lateral velocity is rated with time, it become lateral acceleration. For the purposes of estimation, the simulated result of the lateral motion estimated by Kalman filter-2 is similar to that of acceleration obtained by estimator-2. The estimated value by Kalman filter-1 strongly resembles that of acceleration by estimator-1. The lateral speed estimated by filter-2 has a dense value of estimated numbers around zero. Hence only lateral speed obtained by the dual estimator has a higher error with lower estimated signals near zero with lateral acceleration by estimator-1. Furthermore, applying the third Kalman filter does not improve on the results of dual-Kalman filtering, and is thus not included here.

Reference

- [1] T. Michalek, "Analysis of the influence of the friction coefficient on the guiding behavior", in proceeding of *the 13th conference Applied Mechanics (2011)*, pp. 147–150.
- [2] J. Zelenka, "Running and guiding behaviour of two-axled diesel-electric locomotives," in *New Railway Technique*, vol. 17, no.6, pp. 15–23, 2009.
- [3] J. Zelenka and T. Michalek, "A New Method of the Assessment of Rail Vehicles Guiding Behavior in Small-radius Curves", *International Journal of Applied Mechanics and Engineering*, vol. 15, no. 2, pp.511–519, 2010.
- [4] J. Zelenka and P. Spalek, "Simulations of the guiding behaviour of the locomotive Class 380, assessment of the bogie coupling influence", in proceeding of *the 19th conference with international participation Current Problems in Rail Vehicles*, pp. 195–198, 2009.
- [5] J. Zelenka, J. V'agner, and A. H'aba, "Experimental verificatin of possibilities of determination of flexi-coil springs lateral stiffness", CD 31, 2011.
- [6] K. Zboinski and M. Dusza, "Bifurcation approach to the influence of rolling radius modelling and rail inclination on the stability of railway vehicles in a curved track," *Veh. Syst. Dyn.*, vol. 46, no. sup1, pp. 1023-1037, Sept. 2008.
doi:[10.1080/00423110802037255](https://doi.org/10.1080/00423110802037255)
- [7] K. Zboinski and M. Dusza, "Self-exciting vibrations and Hopf's bifurcation in non-linear stability analysis of rail vehicles in a curved track," *Eur. J. of Mech. A/Solids*, vol. 29, no. 2, pp. 190-203, March-April 2010.
doi:[10.1016/j.euromechsol.2009.10.001](https://doi.org/10.1016/j.euromechsol.2009.10.001)
- [8] P. Kim and J. Seok, "Bifurcation analysis on the hunting behavior of a dual-bogie railway vehicle using the method of multiple scales," *J. Sound Vibrat.*, vol. 329, no. 19, pp. 4017-4039, Sept. 2010.
doi:[10.1016/j.jsv.2010.03.024](https://doi.org/10.1016/j.jsv.2010.03.024)
- [9] P. Kim, J. Jung, and J. Seok, "A parametric dynamic study on hunting stability of full dual-bogie railway vehicle," *Int. J. Prec. Eng. Manuf.*, vol. 12, no. 3, pp. 505-519, June 2011.
doi:[10.1007/s12541-011-0064-1](https://doi.org/10.1007/s12541-011-0064-1)
- [10] M. Ansari, I. Hazrati, E. Esmailzadeh, and S. Azadi, "Wear Rate Estimation of Train Wheels Using Dynamic Simulations and Field Measurements," *Vehicle System Dynamics*, vol. 46, no. 8, pp. 739-759, June 2008.
doi:[10.1080/00423110701586436](https://doi.org/10.1080/00423110701586436)
- [11] A. Asadi and M. Brown, "Rail Vehicle Wheel Wear Pre-diction: A Comparison between Analytical and Experimental Approaches," *Vehicle System Dynamics*, vol. 46, no. 6, pp. 541-549, May 2008.
doi:[10.1080/00423110701589430](https://doi.org/10.1080/00423110701589430)
- [12] R. Lewis, R. Dwyer-Joyce, U. Olofsson, J. Pombo, J. Ambrósio, M. Pereira, C. Ariaudo, and N. Kuka, "Mapping Railway Wheel Material Wear Mechanisms and Transitions," in proceeding of *the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, vol. 224, no. 3, pp. 125-137, March 2010.
doi:[10.1243/09544097JRRT328](https://doi.org/10.1243/09544097JRRT328)
- [13] J. Pombo, J. Ambrósio, M. Pereira, R. Verardi, C. Ari-audo, and N. Kuka, "Influence of Track Conditions and Wheel Wear State on the Loads Imposed on the Infra-structure by Railway Vehicles," *Computers and Structures*, vol. 89, no. 21-22, pp. 1882-1894, Nov. 2011.
doi:[10.1016/j.compstruc.2011.05.009](https://doi.org/10.1016/j.compstruc.2011.05.009)
- [14] I. Hussain, T.-X. Mei, and A. H. Jones, "Modeling and Estimation of Nonlinear Wheel-rail Contact Mechanics," in proceeding of *the twentieth Intenational conference on System Engineering*, Coventry, UK, 2009, pp. 219-223.
- [15] I. Hussain and T.-X. Mei, "Multi Kalman Filtering Approach for Estimation of Wheel-Rail Contact Conditions," in proceeding of *the United kingdom Automatic Control Conference*, Coventry, UK, Sept. 7-10, 2010, pp. 459-464.
doi: [10.1049/ic.2010.0326](https://doi.org/10.1049/ic.2010.0326)
- [16] Z. A. Soomro., "Determination of yaw motion estimation for noise and error value based upon creep coefficient," *NUST Journal of Engineering Sciences*, vol. 7, no. 1, pp. 34-37, 2014.
- [17] Z. A. Soomro, "Step Response and Estimation of Lateral and Yaw Motion Disturbance of Rail Wheelset," *Journal of Engineering and Technology*, vol. 5, no. 1, pp.8-13, 2015.
doi:[10.4103/0976-8580.149473](https://doi.org/10.4103/0976-8580.149473)
- [18] Z. A. Soomro, "Correlation of Lateral and yaw analysis responses to tracking of linearized rail wheelset model". *Journal of Mechanical Engineering and Technology (JMETS)*. vol. 7, no. 1, pp. 31-41, 2015.
- [19] Z. A. Soomro, "Development of Onboard Adhesion Identification System for Railway Vehicles", PhD thesis, Mehran University of Engineering & Technology, Jamshoro, Pakistan.

