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Modern Condition Monitoring Systems for Railway Wheel-Set Dynamics: Performance Analysis and Limitations of Existing Techniques

Khakoo Mal[1, 2], Imtiaz Hussain[3], Tayab Din Memon[4, 5], Dileep Kumar[1], and Bhawani Shankar Chowdhry[1]

[1]*NCRA Condition Monitoring Systems Lab, Mehran University of Engineering and Technology, Jamshoro, Sindh, Pakistan*
[2]*Sukkur IBA University, Sukkur, Pakistan*
[3]*Department of Electronics and Power Engineering, Pakistan Navy Engineering College NUST, Karachi, Pakistan*
[4]*Department of Electronic Engineering, Mehran University of Engineering and Technology, Jamshoro, Pakistan*
[5]*School of Information Technology and Engineering (SITE), Melbourne Institute of Technology, Melbourne, Australia*

Correspondence Author: Dileep Kumar (dileep.kumar@admin.muet.edu.pk)

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Abstract

The rapid rise in railroad transport across the world demands an improved service in form of safety, comfort, reliability, and cost-effectiveness. For the improvement of reliability, safety, and efficiency; sophisticated Condition Monitoring Systems (CMS) have become an important part of modern railway operations. CMS for railway vehicles involves techniques including model-based and signal-based techniques for the detection of faults. These techniques assist in preventing the system from any major failure. The core element of a CMS is the use of suitable algorithms to evaluate system behavior for achieving a solution to avoid accidents of railway vehicles. This paper attempts to compare and evaluate the existing state-of-the-art condition monitoring techniques applied for real-time monitoring of railway wheel-set dynamics. In addition, recommendations are presented for future research efforts in this area.

Index Terms: *Condition Monitoring Systems, Wheel-Rail Contact, Wheel-Set Dynamics, Model-Based Method, Kalman Filter.*

I. INTRODUCTION

From a sustainable development point of view in today's society, the mode of transport that seems to be least harmful to the natural environment is railroad transport because it emits less carbon dioxide as compared to its tonnage capacity, which is one of the causal agents of global warming than other automobiles [1]. State of art railway vehicles utilizes advanced schemes to monitor the dynamic behavior of a train for the identification of faulty conditions. The dynamic performance of the entire rolling stock is controlled by the forces generated between wheel and track, therefore the wheel-rail interaction area is a very important part of rolling stock. Any variations e.g. wear, fatigue, etc. in the profile and status of either the track or wheel will have consequent variations on the response of the railway vehicle.

For stable operation of the railway wheel-set factors such as adhesion at the wheel-rail interface, wheel profile, rail profile and track irregularities should be within predefined limits [2] and [3]. The railway vehicle performance can be severely influenced if they deviate from a standard level. Hence these parameters, their interaction, and Interdependency are necessary to examine for obtaining real-time information in order to develop suitable condition monitoring strategies.

Reliable identification of adhesion limit, wheel-track interface force properties for traction/braking controls, and wheel conicity levels without the use of expensive equipment has been a tough technical challenge in railway research. A lot of research work is being conducted in said area.

It may be required to identify the real-time information of track status for re-adhesion by traction and braking control systems. The work is being continued by different researchers [4-7] across the globe for designing, verifying, and implementing the proactive systems for estimation and identification of real-time railway track conditions in order to prevent slip in acceleration and slide in braking of trains. A Kalman filter-based method is proposed for estimation of low adhesion and wheel-rail profile by taking the forces of wheel-track interface and conicity [8]. An estimation method using the Kalman filter is also offered to detect the creep by analyzing the torsional vibrations in the wheel-set axle [9]. The estimations of real-time adhesion conditions and wheel slip are proposed by using a bank of Kalman filters [10] and [11]. Indirect methods using Kalman-Bucy filter are designed for identification of real-time wheel-rail interaction status to detect wear and tear in wheel and track as well as low adhesion conditions. The output residuals from all Kalman-Bucy filters were evaluated by taking a Fuzzy logic decision mode, the estimators offer the finest comparison to the current operating condition and therefore provide track condition information in real-time. A technique based on Kalker's linear theory and Heuristic non-linear contact model is presented for simulation-based modeling of dynamic conduct of wheel-rail interface to determine the profile of interface area and for determining the tangential interface forces developed in contact patch [12] and [13]. By using parameter measurement of traction motor, creep forces between wheel and roller can be estimated by using Kalman filter [14] and slip-slide can be identified by taking Extended Kalman filter (EKF) [15]. A system based on model approach taking Kalman-Bucy Filter and non-model technique taking direct data examination is proposed to estimate low adhesion status [16] and [17]. Low adhesion mechanism under various contaminants is dealt with by researchers [18]. The Test rig results of the numerical model show that the presence of water, oil, and leaf contamination on a rail, high vehicle speed, and high relative humidity, causes the reduction of the adhesion coefficient. An estimation method using an Unscented Kalman filter is offered to predict creep, creep forces, and friction coefficient by using the traction motor behavior [19]. A scheme using the methods and principles of synergetic control theory is offered to estimate adhesion moment in interface patch of wheel and track [20]. The use of a synergetic method solved the trouble of evaluating adhesion value in wheel-rail contact patches that cannot be measured directly. An inverse wagon model of two dimensions using acceleration is designed for the assessment and monitoring of wheel-track interface forces [21]. Another technique based on the multi-rate EKF state identification is proposed to estimate the slip velocity by combining the multi-rate method and the EKF method in order to detect the load torque of the traction motor [22]. A signal-based technique is proposed to know the conicity level and to analyze the effect of change of conicity level on wheel-set dynamics [3]. An optimization method for the railway wheel profile based on the Weibull distribution function is proposed to enhance the overall adhesion coefficient available at wheel-track contact [23]. Low adhesion issues supposed to be developed by tree leaves in the wheel-track interaction are shown [24]. Analysis outcome relates to the information show that wet leaves in the interaction region develop very little friction coefficients e.g. less than 0.1 value. Extended Kalman Filter using a fitting nonlinear model may be used to estimate the contact forces and moments in wheel-rail contact which uses considerably in nonlinearities of the interface [25]. An efficient and simple algorithm that uses in the time domain is presented to detect wheel flat errors taking the measurement of vertical acceleration in axle-box [26]. The technique can be fabricated on a monitoring scheme for on-board practice and can be implemented on light hardware architecture. Three model-based techniques, two in the time domain and one in the frequency domain are proposed for the identification of geometric lateral and cross-level rail disturbances from the measurements of acceleration taken through onboard trains without using costly and compound optical measurement tools [27].

Results of the numerical experiment show that two techniques (one in time domain based on Kalman filter or KF and frequency domain techniques) deliver precise outcomes even in the existence of a high level of measurement noise. In this paper, indirect condition monitoring techniques will be analyzed and evaluated for predicting the real-time information of wheel-rail contact conditions and associated parameters which influence the performance of railway operations.

In Section II, the problems of wheel-track contact conditions and interrelated dynamics will be elaborated which severely affect the performance of railway vehicles. Modern condition monitoring techniques, mainly comprised of model-based and signal-based approaches, for detecting, estimating, and identification of railway wheel-set dynamics will be discussed in Section III. Field testing of wheel-track contact condition monitoring techniques will be presented in Section IV followed by concluding remarks in Section V.

II. PROBLEMS OF RAILWAY WHEEL-SET DYNAMICS

The key component of any analysis on railway vehicle performance is the contact patch between wheel and rail. The contact patch or area of contact is formed when elastic deformation occurs due to normal load between wheel and track [2]. All the forces that support and control the rolling stock transfer through this small wheel-rail interface point and for the study of any rolling stock behavior, it is very important to know the nature of these forces [28]. Figure 1 shows the wheel-rail interface which faces challenges during railway vehicle operation.

Figure 1: Wheel-Rail Interface

The wheel-set dynamics that affect the performance of railway operation can broadly be divided into main two categories; i.e., wheel and rail profiles and wheel-rail interact conditions:

A. Wheel and Rail Profile Issue

Wheel-rail guidance is made possible by the shapes of wheel and rail profiles [29]. The cross-sections of both wheel and track are stated as profiles which are the foundation of interaction structure issues in the wheel-track structure [23]. Wheel profile affects the performance of railway vehicles' dynamic behavior, stability, and ride of comfort. Small variations in the profile shape outcome significantly influence the contact geometry features of wheel and track, thereby changing the dynamic performance as well as derailment safety of railway vehicles. Therefore, real-time identification of changes in wheel and rail profiles is necessary in order to make a strategy to avoid negative impacts on railway operation. Conicity relating to wheel profile is the characteristic that describes the tendency of wheel to role like a cone. Trains are mostly kept inside the tracks through the conicity of the wheel. Conicity is the primary mode of guidance for small wheel displacements from the center of a straight or slightly curved track [28]. Even a minor change in conicity value may cause a significant fault in wheel tread as well as in rail [3]. When the conicity level increases beyond the limit then the frequency of wheel-set kinematic oscillation expressed in Eq. (1) increases, which causes discomfort for passengers.

$$f = \frac{V\sqrt{\gamma/Lgr0}}{2\pi} \tag{1}$$

When the conicity level decreases below the predefined value (say 0.05 radian), it shows wheel tread is worn out and it became nearly cylindrical in shape. The cylindrical wheel tread has not had the capacity to bring into the line itself back at the middle point. Therefore, a defined range of conicity is appropriate to be railroad processes safe, vibration-free, and noise-free [3].

In a train, the dynamic reaction of the structure is directed by the imperfections in the rail path [4]. Rail disturbances are the major cause of vehicle vibration. With high speed, track disturbances have become a more significant matter. Knowledge of track irregularities is highly important for the railway system. The identification of variation in wheel and rail profiles and track irregularities is difficult and these parameters cannot be measured or identified directly.

B. Wheel-Rail Interaction Conditions

The wheel-rail interface forces control the movement of railway vehicles, which vary nonlinearly with respect to slip ratio and are deviated by the random changes in adhesion levels. Adhesion is one of the greatest noteworthy aspects affecting the dynamic behavior of the wheel-set [2]. Adhesion is the tangential force in the wheel-track interaction that wheels possess [18]. Adhesion coefficient is a tangential force to normal force ratio and classically presumed as a function of creep [23]. Creep is assumed to be while wheel differs from pure rolling, which the space is taken by the wheel in one round is different from the wheel circumference. Figure 2 shows a typical nonlinearity in the adhesion coefficient with respect to the slip ratio for a dry wheel-rail contact. This creep curve is divided into three regions in order to describe the stability behavior of the wheel-set. The starting portion of the curve is linear and the vehicle operates in steady conditions, in the second part of the curve the slip region at the contact area increases when the tractive effort is increased. In the third part of the curve, tractive force shoots on its saturation value and the whole wheel-rail interface region comes in a position of pure sliding, resultantly the vehicle will be unstable.

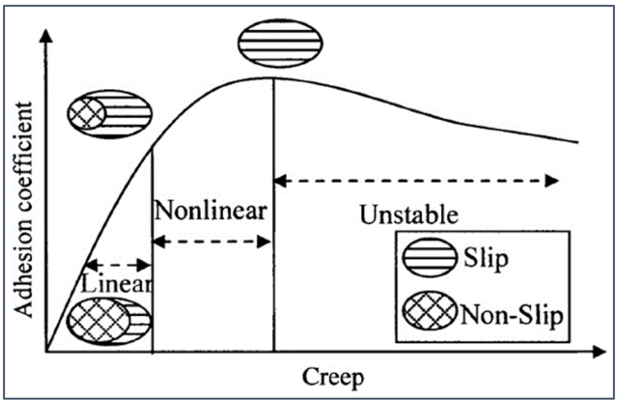

Figure 2: Creep V/S Adhesion Coefficient [2]

It can be seen from the above figure that at the wheel-track interface, a fraction of the adhesion coefficient is essential for the transmission of applied force exerted by the control system in railway engines. The applied force might surpass the highest adhesion force present between the wheel and track contact, causing the development of slip in accelerating or skid in decelerating modes [2]. The developed slip or slide mainly disturbs the regular processes of the railway system. Majorly, it rises maintenance budget, unwanted wear of wheel, and rail surfaces, and results in an increased safety risk.

A low adhesion condition is an issue related to a track head that has small friction or low traction in the wheel-track interface. Typically, the adhesion coefficient between the wheel and track contact area is 0.4 in dry situations. However, the track level is normally contaminated with third body material such as water, oil, soil, and ice, which reduces the adhesion coefficient to 0.1 or even less than that in some situations [24]. Along with low adhesion conditions, wheel-track interaction forces have major impacts on rolling stock operation.

The wheel-track interaction forces that regulate the dynamics of rolling stock are creep forces. Creep forces are generated in reaction to creepages. Creep forces are affected by many factors including rolling stock velocity, nonlinear wheel, and track profile, nonlinear adhesion level, rail profile, suspension factors, and affect the wheel-set dynamics. The creep forces and adhesion forces are very much interrelated and interdependent by the following equation [2].

$$F_i = u_i N_i \qquad i=L, R \tag{2}$$

F, u, and N represent creep force, adhesion coefficient, and normal force, respectively. L and R stand for left and right wheels. Above mentioned wheel-rail contact conditions cause problems in railway vehicle operations. For example, station overruns, signal pass at danger (SPAD), collisions occurrence, or even derailment type incidents can occur. The wheel-track adhesion and governing forces can barely be measured directly. Different approaches are usually adopted to measure and identify the adhesion between wheel and rail. For example, using instrumented trains, hand-pushed tribometers, vehicle-based tribo-railer, and the pendulum rig are used to measure the adhesion level. However, these methods are difficult to implement, expensive, and are not capable to identify the adhesion correctly [18]. A lack of accurate knowledge about the issue of low adhesion conditions is a significant reason why contaminated paths are still an issue. This makes it difficult to take effective and capable actions [2]. The need to improve adhesion conditions has been a long-standing issue, which can give responses to better operating performance as well as a reduction in expenditures. Studies have been carried out over a long time, but still, no definitive solution is found to improve the low adhesion conditions as the adhesion coefficient is very sensitive to environmental situations, train features, contact surface contamination, and weather. It can also change unpredictably from site to site rapidly [2]. For improving the low adhesion condition problem, various methods have been considered and applied. For example, friction adjustment, track cleaning, vegetation, applying 'Sandite', and the use of water jets. These methods have helped to some degree, but this is still insufficient to manage the issues caused by bad adhesion conditions as the option of an appropriative action for such circumstances is hard [2]. Table 1 summarizes the wheel-rail contact condition issues that influence to performance parameters of railway vehicles. Indirect methods based on scientific approaches are proposed by different researchers and will be discussed in Section III.

In Section III, condition-based approaches to measure and identify the wheel and track profiles and wheel-rail interface conditions in real-time to increase the sustainability of railway transport will be discussed.

III. MODERN CONDITION MONITORING TECHNIQUES FOR RAILWAY WHEE-SET DYNAMICS

Condition monitoring is the procedure of observing the state of a scheme in real-time and its usage permits maintenance to be planned or other activities to be used to prevent the adverse results of the fault before the fault occurs [2]. Condition-based maintenance is considered more efficient because it eliminates chances of over and under maintenance, reduces waste of replacing components that still are in working condition, and improves ease of access and safety by physical analysis of railway vehicles [31]. The generic condition monitoring carries an out certain degree of information of a concerned system. Figure 3 (a) and (b) show the block diagrams for a general condition monitoring scheme and railway wheel-set condition monitoring system respectively.

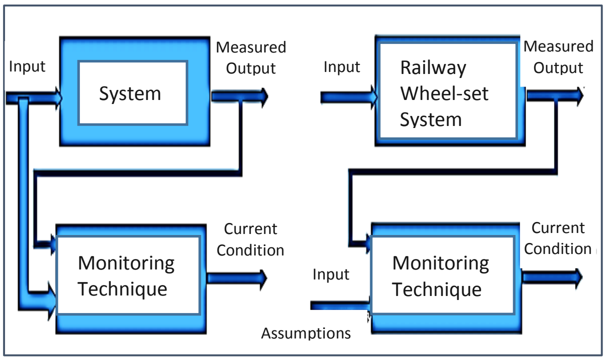

Figure 3: Block Diagrams for (a) General Condition Monitoring, (b) Railway Wheel-set Condition Monitoring

In Figure 3 (a) the controlled input and measured response for the scheme are fed to the condition monitoring approach, while in Figure 3 (b) the dynamic reaction of the railway wheel-set is run by rail irregularities. Hence, track irregularities are not controlled inputs. The direct outcome from wheel-set can be acquired with a more processing set of rules to create a state or sort of fault detection [8].

From previous work, it can be seen that the most interesting dynamic parameters are low adhesion force between wheel and rail, wheel and track profiles, and track irregularities, as these significantly affect the performance of a railway vehicle. A number of concepts have been offered by different researchers to identify the running conditions of the wheel-track interaction indirectly in order to make intelligent strategies in the traction control system.

Table 1: Summary of Wheel-Track Interface Conditions and Affecting Parameters of Railway Vehicle

S. No.	Affecting Factors	Performance Parameters to be Affected
1	Low Adhesion Condition	Wheel slip in acceleration and slide in braking, even derailment may occur in severe conditions
2	Variations in Wheel Conicity Level	An increasing conicity level beyond the upper limit causes an increase in kinematic oscillation, which results in the rise of discomfort. On the other hand, a decrease in conicity below the predefined value loses the wheel's capacity for aligning back at its center position
3	Creep Forces	Affect Adhesion force and other wheel-set dynamics
4	Wheel and Rail Profiles	Variations in wheel and rail profiles affect a vehicle's dynamic behavior, stability, and rise of comfort. These even cause derailment
5	Track Irregularities	Track irregularities are the main source of vehicle vibration. In high speed, track irregularities become more concern

The following are some modern CMS schemes for indirect and real-time estimation of wheel-set dynamics; i.e., Model-based schemes, Signal-based schemes, and Other CMS schemes:

A. Model-Based Schemes

The model-based technique is chosen when parameters are not measured directly, but the association between input and output signals can be made [30]. These approaches depend on matching estimated and measured scheme response values. The feature found after this matching is termed as residual and it is the sign of the existence or unavailability of a fault [31]. The residual evaluation scheme is shown in Figure 4.

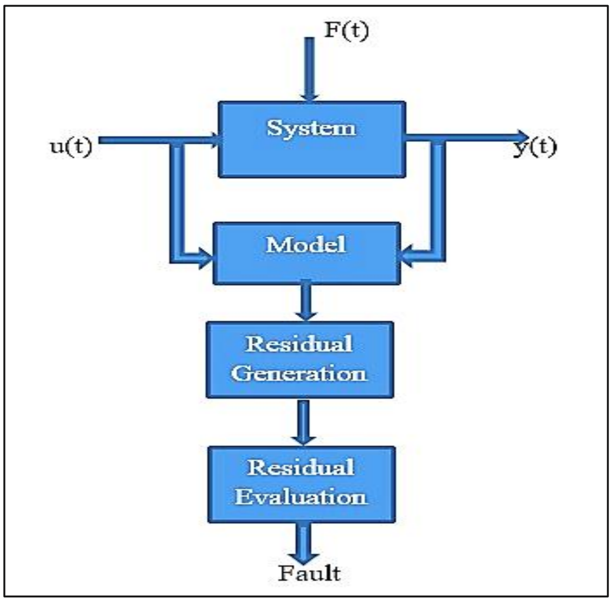

Figure 4: Residual Evaluation in a Model-Based CMS System

In this section, the model-based estimation techniques will be reviewed which present on-board monitoring methods applied for the estimation of dynamics of wheel-set [32]. Model-based estimation schemes for wheel-set dynamics are divided into two groups in the account of algorithms i.e., Kalman filter and its extension forms and other model-based algorithms.

i. Kalman Filter and its Extension Forms:

Possibly the most recognized method in model-based approaches is the observer-based error detection technique that can identify a fault in the sensor, actuator, and system unit effectively. The generally surveyed technique to estimate the dynamic schemes which take an observer to detect fault is the Kalman filter for linear arrangements [30]. The Kalman filter is one of the most famous approaches taken for the estimation of state and parameter. Kalman filter utilizes linear measurements associated with the state and error covariance matrices to produce a 'gain' known as 'Kalman gain'. The estimation procedure runs in a predictor-corrector fashion for keeping a numerically least state error covariance matrix [30]. The recursive nature of the Kalman filter is one of the very interesting aspects, this feature forms real-time implementations much more viable than other algorithms. Figure 5 illustrates the block diagram of the Kalman filter with a general system.

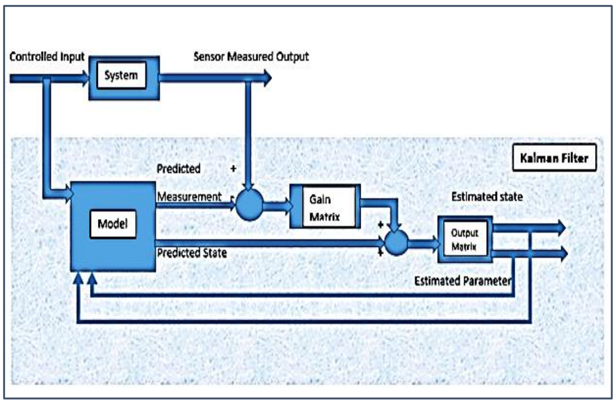

Figure 5: Block Diagram of the Kalman Filter with General System

Due to its simplicity and robust nature, the Kalman filter has been a matter of wide research and has been used widely in different applications, e.g., parameter and state estimations of railway systems, navigation, and tracking in interactive computer graphics. From the existing available model-based research on condition monitoring of railway systems, more than 50% of the reported work is based on Kalman filtering algorithms.

Model-based CMS using Kalman filter is applied for estimation of wheel-track geometry and low adhesion by taking conicity and wheel-track contact forces respectively [8]. A Kalman filter is used to detect wheel slip as well as make a re-adhesion controller based on the examination of torsional vibrations in the wheel-set axle [9]. A method using Kalman filter is presented for an estimate of creep force as well as wheel-track creep, simulation outcomes have revealed that error is minor and the estimate of friction coefficient is correct [14].

A model-based method taking Bucy-Kalman filter is used to estimate the creep forces of a full vehicle model for detecting the local adhesion conditions and predicting the wear produced on the rail and vehicle [12]. Multiple Bucy-Kalman filters are used to develop an onboard method for real-time identification of wheel-rail contact conditions in order to signify changes in adhesion level and other interface conditions. The output residuals from all Kalman Bucy filters are evaluated using a Fuzzy logic decision-making approach to offer real-time knowledge about rail position [2]. A model-based CMS approach using Kalman-Bucy filter is proposed to estimate creep forces with consequent post-processing for interpretation into adhesion levels [17].

The Kalman filter deals with the issue of a linear process, but what occurs if the process to be estimated is non-linear? The extension form of the Kalman filter, used for non-linear processes to be estimated, is the EKF. The EKF does linearization in current mean and covariance by evaluating Jacobian matrices and their partial derivatives. An approach using EKF for indirect detecting and estimating creep, creep force, as well as friction coefficient, is proposed, after estimation re-adhesion controller is developed to control the motor torque command according to the highest existing adhesion based on the estimated outcomes for better utilization of available adhesion. Numerical simulations under different friction coefficients show the validation of the proposed method [15]. A condition monitoring technique using EKF for wheel-set driven by AC Induction motor is proposed to make an effective re-adhesion controller by matching the estimated and real values of the induction motor’s parameters [33]. After that, the torque of an electric motor with adhesion force is computed indirectly from estimated facts in order to develop a scheme in real-time for detection of local adhesion conditions and prediction of wear produced. The CMS technique based on EKF is proposed to estimate the interaction forces and moments in wheel-track contact which uses considerably in nonlinearities of the interface. The scheme has been successfully verified by simulations with SIMPACK software in all adhesion conditions and in the existence of changing coefficient of friction [25] and [33].

For non-linear systems, the EKF is one of the most famous approaches but it can also present huge errors when the system is highly non-linear, an Unscented Kalman filter (UKF) is then better to avoid any linearization by utilizing a deterministic approach. An estimator using UKF is established to monitor the real-time friction coefficient at wheel-roller contact of roller rig by carrying out measurements with and without impurity on a wide band of creepage by changing the traction load. The performance of the estimator has been evaluated by carrying out a series of experiments on a designed roller rig [24].

In the above analysis, model-based CMS techniques using discrete Kalman filter or simple KF, Bucy-Kalman filter (the continuous-time counterpart of Kalman filter), EKF (an extended form of Kalman filter for the non-linear process), and UKF (an extended form of EKF for the highly non-linear process) have been reviewed for detecting and estimating wheel-set dynamics. All these four filters are summarized in the below table.

ii. Other Model-Based Algorithms:

Some other model-based CMS techniques are also suitably good for detecting and estimating the dynamics of railway wheel-set. A method based on Kalker's linear model and Heuristic non-linear model for simulation-based molding of dynamic conduct of wheel-rail interface is presented to estimate critical forward velocity [13].

The results simulated through MATLAB compared well with the estimated results, so the proposed method was validated. A scheme using the approaches and principles of synergetic control theory is presented to estimate adhesion moment in interface patch of wheel and track [20]. A two-dimensional inverse wagon model is developed based on accelerations for estimation and monitoring of wheel-track interface forces [21]. The VAMPIRE wagon simulation model is taken for simulation and verification of inverse modeling; finally, the model is simplified into the one-dimensional vertical model for possible online applications.

Table 2: Summary of Four Kalman Filters used for Estimating Wheel-Rail Interaction Dynamics

Filter Type	Basic Principle	Strength	Limitation	Used in CMS for Wheel-Set Dynamics
Discrete Kalman Filter	Developed for estimating unmeasured states of linear discrete-time processes	Uses a two-step predictor-corrector algorithm to update the state estimates. It is most optimal, hence it is most popular than others	Inefficient in non-linear processes	In [8, 9, 14] used to estimate, detect and identify the wheel and rail profiles, low adhesion, wheel slip, creep force, creepage, and friction coefficient
Bucy-Kalman Filter	Developed for estimating unmeasured states of linear continuous-time processes	Uses a differential Riccati equation to be integrated over time	Inefficient in non-linear processes	In [2, 12, 17] used to estimate, detect and identify the wheel and rail profiles, low adhesion, wheel slip, creep force, creepage, friction coefficient, and wheel and track wear
Extended Kalman Filter	Developed for estimating unmeasured states of non-linear discrete-time processes	Uses a two-step predictor-corrector algorithm to update the state estimates. Jacobian matrices are used for linearization	Inefficient in highly non-linear processes	In [15, 25, 33] used to estimate, detect and identify the wheel and rail profiles, low adhesion, wheel slip, creep force, creepage, friction coefficient and wheel, and track wear
Unscented Kalman Filter	Developed for estimating unmeasured states of highly non-linear discrete-time processes	UKF is simpler to apply in the exercise as no critical derivatives are essential to be found. A chain of sigma points are selected then spread over the real nonlinearity of the scheme	Little bit complex	In [24] used to monitor the friction coefficient at wheel-roller contact of roller rig

A model-based three different techniques two-run in time-domain and one in frequency-domain proposed to identify the geometric track disturbances from the measurements of acceleration obtained through on-board trains without using costly and compound optical measurement tools. Numerical experimental results show that two techniques (one in time domain and frequency domain techniques) deliver precise outcomes even in the existence of great measuring noise [27].

B. Signal-Based Schemes

When simply output signals are present in the scheme, a signal-based technique is suitable for condition monitoring [31].

The main object of signal-based approaches is to know the difference between defective and defect-free systems from the scheme response signals with no mathematical model in the error identification procedure. In signal-based approaches, measured signals may be analyzed in the time domain, frequency domain, and in both time and frequency domains, furthermore, these measured signals can be analyzed with help of filters, a spectral analysis, or wavelet technique [32].

When the signal is processed, so matched with a prebuilt fault situations database got from simulations or experimental testing [31].

A signal-based predictive maintenance strategy is proposed to know the wheel conicity level and to analyze the effect of conicity level change on wheel-set dynamics [34].

The block diagram of the proposed scheme is shown in Figure 6 below.

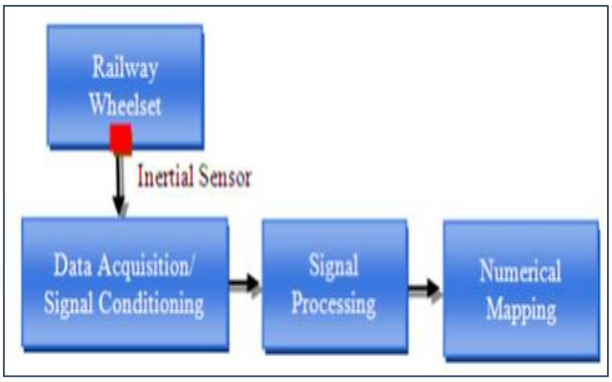

Figure 6: Block Diagram of Signal-Based CMS for Wheel-set [34]

In the presented technique, both yaw and lateral dynamics of the wheel-set are measured by using inertial sensors, and the status of the wheel-set is estimated indirectly by exploiting the measured dynamic response. Kinematic Oscillation of the running wheel-set is determined and analyzed through the Fast Fourier Transform technique. Further, a diagnostic tool using wavelet transform is presented to detect wheel flat defects of the test vehicle [30]. This method was observed to have a high capability in identifying deteriorated wheels and measuring the vehicle speed.

C. Other CMS Schemes:

Other than model-based and signal-based condition monitoring techniques are also being deployed by different researchers to estimate and detect the wheel-rail interaction dynamics.

The development of an 'On-line' and 'Off-line' hybrid contact algorithm is presented for modeling wheel-track interaction issues using the elastic contact formulation in order to analyze the multibody railroad vehicle systems [35]. In this hybrid algorithm, off-line tabular search is applied to predict the position of tread interaction patches, whereas online iterative search is applied to predict the location of flange interaction patches. An optimization technique based on the Weibull distribution function was presented for wheel profile to raise the overall adhesion level available between wheel and rail contact area [23]. The research emphases on the geometric mixture of the wheel as well as track profiles to formulate in what way the interaction region can be optimized to improve the level of adhesion. About the hunting instability problem arising in high-speed trains, a CRH2C vehicle model (one of the high-speed train models in China) is built-in for studying the stability based on the wheel-rail interface analysis [36]. It is found by authors that if the equivalent conicity curve is more concave then more nonlinearity may be observed on the wheel-track contact that causes an effect severely on the nonlinear stability. An algorithm to detect wheel flat errors taking the measurement of vertical acceleration in axle-box is described [26]. The technique is appropriate to refer to an index to find out the existence of wheel flats at the initial stages as well as to estimate the degree of the issue. The outcomes of both experimental as well as simulation tests, refer that the wheel flat index offered in the research scheme can identify minor flats and can estimate their gravity.

In subsections 3.1, 3.2, and 3.3 different condition monitoring techniques have been evaluated, the summary is tabulated as under:

Table 3: Summary of Evaluated Condition Monitoring Techniques for Wheel-Rail Interaction Dynamics

Citation	Approach / Algorithm	Uses in the Railway System	Remarks
G. Charles et al [8], 2008	Model-based using Discrete Kalman filter	Estimation of wheel and rail profiles and low adhesion by taking conicity and wheel-rail interaction forces respectively	Further design and analysis are required for robustness in both applications
TX Mei et al [9], 2008	Model-based using Discrete Kalman filter	Wheel slip detection and making re-adhesion control by inspecting the torsional vibrations in the axle of the wheel-set	The effectiveness of the proposed technique is demonstrated using computer simulations
H. Sugiyama et al [35], 2009	On-line and Off-line hybrid contact algorithm	Modeling wheel-rail contact to locate the wheel-rail contact patch	Numerical simulation was carried out to demonstrate the use of the contact algorithm developed in the investigation
Christopher P. Ward et al [12], 2011	Model-based using Bucy-Kalman filter	Estimation of creep forces to identify the local adhesion conditions as well as to predict wear produced on the rail and vehicle.	Further work may be carried out in order to translate the estimated parameters into a useful understanding of the adhesion conditions by using the scale roller rig with MBS (Multi-Body System) simulation software for validation
R W Ngigi et al [30], 2012	Signal-based using Wavelet transform	Detecting wheel flat defects	Further work is required to be investigated in the depth of the proposed method
I. Hussain [2], 2012	Model-based using Bucy-Kalman filter	Real-time identification of wheel-rail contact conditions to signify changes in the level of adhesion level and other diverse interface conditions	Being nonlinear behavior of wheel-track dynamic conduct, the Bucy-Kalman filter is hard to use for whole operating conditions. Hence work further may be carried out by using EKF or UKF
Zhao Y. et al [14], 2012	Model-based using Discrete Kalman filter	Estimation of the creep force and creepage to identify the friction coefficient	The results of RMS (root mean square) values of the residuals used to identify friction coefficient are showing small error, hence the proposed technique was found robust

A. Anyakwo et al [13], 2012	Model-based using Kalker's linear model and Heuristic non-linear model	Simulation-based Molding of dynamic conduct of wheel-rail interface for estimating critical forward velocity	This approach can be suitable in the future in the advancement of smart diagnostic structures and condition monitoring schemes
Zhao Y. et al [15], 2013	Model-based using Extended Kalman filter	Indirect detecting and estimating creep force, creepage, and friction coefficient then designing of the re-adhesion controller.	The proposal is validated by carrying out simulations under different friction coefficients. Further testing is required on the roller rig for verifying the results in real-time.
Peter D. Hubbard et al [17], 2013	Model-based using Kalman-Bucy filter	Estimation of creep forces with subsequent post-processing for interpretation into adhesion levels	The approaches have been verified by carrying out simulations on MBS software VAMPIRE
Zhao Y. et al [19], 2014	Model-based using Unscented Kalman filter	Monitoring the friction coefficient at the wheel-roller interface in real-time by carrying out measurements with and without contamination on the large range of creepage	The performance of the estimator is evaluated by carrying out a series of experiments on the roller rig
Radionov I. A et al [20], 2015	Model-based using synergetic control theory	Estimation of adhesion moment in contact patch of wheel-railway	By knowing current information about adhesion conditions through the proposed method, a very accurate adaptive control scheme can be constructed for electrical drives of the train engine
Yan Quan Sun et al [21], 2015	Model-based using two-dimensional inverse wagon model	Assessment and monitoring of wheel-track interface forces	With the reasonable agreement achieved in comparison between predicted and simulated forces, the outcomes at greater speed are affordable. Enhancement in the model is more required to decrease the error on speeds of expectation
Khurram Shaikh et al [34], 2021	Signal-based using FFT analysis	Knowing the wheel conicity level and analyzing the effect of conicity level change on wheel-set dynamics	FFT is a very basic analysis tool, hence advanced signal processing techniques like wavelet transform or Hilbert transform would be suitable in real-time signal analysis
B. Liu et al [23], 2016	Weibull distribution function	Emphases on the geometric mixture of the wheel as well as track profiles to formulate in what way the interaction point can be optimized to improve the level of adhesion	The obtained optimized profile has been incorporated in the complete vehicle multi-body system model to assess the dynamic performance of vehicle structure and found that the dynamic characteristics of the train have not deteriorated but in some cases are improved
K. Mal et al [33], 2020	Model-based using Extended Kalman filter	Calculate and estimate adhesion force and other lateral dynamics	It has been proved by carrying out a simulation that the offered EKF estimator has a dominancy in estimation during varying interface conditions
K. Mal et al. [25], 2021	Model-based using Extended Kalman filter	Estimating the non-linear wheel-set dynamics under varying adhesion conditions	The scheme has been successfully verified by simulations with MATLAB software. EKF was employed for estimating wheel-set dynamics under varying adhesion conditions
L. L. Xing et al [36], 2018	The CRH2C vehicle model is developed	Examining the stability using wheel-track interface study	Concluded by authors after evaluation that if the equivalent conicity curve is more concave then more nonlinearity may be observed on wheel-track contact that causes an effect severely on the nonlinear stability. So, further work on concave of equivalent conicity is suggested to overcome its adverse effect
N. Bosso et al [26], 2018	Algorithm defined index	Discovering the existence of wheel flats at the initial stages by taking the measurement of vertical acceleration in axle-box and estimating the gravity of the issue	For validating the algorithm experimental as well as simulation assessments have been made on a freight train and found robust. Further, the technique is sufficiently simple to be applied even on wireless monitoring schemes using a low-power microcontroller
A. De Rosa et al [27], 2019	Model-based using three techniques, two in the time domain and one in the frequency domain	Detection of geometric rail irregularities from the measurements of acceleration, two techniques (one in time domain and one in frequency domain techniques) deliver precise outcomes even in the existence of great measuring noise	The methods are less viable for uses on small distances or metropolitan tracks, in which speed changes of running vehicles are important. Hence further investigation may be done for its feasibility for short distances too

D. Implementing platform:

It is very essential to keep in mind the real-world features of condition monitoring techniques being evaluated for wheel-rail interaction dynamics. Otherwise, the entirety of the designs or algorithms will be useless if they cannot be implemented easily [2] and [37]. Integrated electronics systems like microcontrollers, digital signal processors, and embedded systems e.g., Application-Specific Integrated Circuits (ASICs) or the Field Programmable Gate Array (FPGA), are some platforms to implement condition monitoring techniques in real-time. Inertial sensors such as the accelerometer and gyroscope with necessary electric power arrangement are required to be interfaced with electronic systems with due care for onboard applying wheel-set dynamics monitoring techniques. On the prototype level, the FPGA is a good platform being adaptive and reprogrammable and is being used by different researchers in wheel-rail condition monitoring experiments.

IV. PROBLEM STATEMENT AND ITS PROPOSED SOLUTION

Field testing of condition monitoring techniques in wheel-set dynamics Condition monitoring awareness within railway production has increased in the modern age [30]. The condition monitoring techniques or algorithms firstly should be feasible to integrate on a monitoring system board or module for further implementation in real-time. After testing the railway condition monitoring system in the laboratories for verifying the signals and their elaborations under certain circumstances, secondly, it is required to test it on a real rolling stock where a series of experimental activities are to be performed for verifying the algorithms in various working or failure situations [37] and [38].

In Figure 7, the railway condition monitoring system is connected on a modified freight train, this installation did not need an alteration in the railway freights structure. ‘Peschici-S. Severo’ railway track is taken for testing which is a secondary railway track in Southern Italy run by Ferrovie del Gargano, a line of 78-kilo meter long, contains small radii curves, has a 1435 mm track gauge. No severe abnormalities or faults have been identified throughout the tests on the running behavior of the vehicle and its modules.

Figure 7: Freight Train Connected with the Monitoring System in the Tests on the ‘Peschici-S. Severo’ Train Track [37]

The condition monitoring techniques for train and track have been analyzed in Poland and validated through the remotely installed real-time monitoring system software, snapshot of the software window is appended in Figure 8 [1].

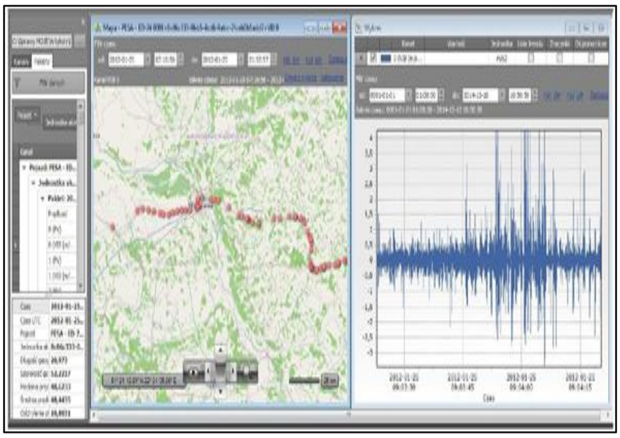

Figure 8: Snapshot of the User Subsystem Software in the Rail Vehicle and Track Monitoring System [1]

The wheel flat identification algorithm has been implemented on a monitoring scheme and is tested experimentally for its validation on the Velim test circuit (consisting of two large standard gauge railway track ovals designed for continuous running of new rail vehicles) in the Czech Republic as shown in Figure 9 [26]. Three different model-based approaches (two-run in time domain and one in frequency domain) for estimation of lateral and roll rail irregularities are presented [27]. The real vehicle DIA.MAN.TE Italian train and real track Torino-Milano High-Speed Line have also been tested to validate all three different model-based condition monitoring approaches.

Figure 9: Railway Cargo Used in the Tests with Installed Monitoring Scheme [26]

V. CONCLUSION AND RECOMMENDATIONS

Extensive use of railway infrastructure and rolling stock due to the increase in railway traffic worldwide is putting lots of pressure on railway operators to enhance the safety and reliability of railways systems. Conventional methods (scheduled or time-based maintenance) are inefficient and cost a huge amount of money due to longer downtimes. The state-of-the-art smart railway system depends on advanced monitoring schemes to permit up-to-date decision-making on asset managing activities, particularly during maintenance and renewal actions. In this paper, a review of the condition monitoring methods that are applied for wheel-set dynamics. It attempts to address the challenge of identifying the right condition monitoring algorithm for detecting wheel-set dynamics, which further can be interpreted in a suitable data system to make it in controlling or maintenance strategy. The presented condition monitoring techniques focus on the detection and identification of wheel-rail problems, e.g., low adhesion condition, detection of wheel profile, wheel flat defects, and some of condition monitoring methods perform the detection of track irregularities. This paper attempts to compare and evaluate analytically the condition monitoring methods applied for wheel-set dynamics and interrelated issues. However, model-based estimation techniques are used by most researchers and are found to be robust. It is further observed that the model-based estimation techniques comprising of Kalman filter and its extension forms because in Kalman filters no storing mechanism is required, just in iterative process previous data is being stored and updated.

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Authors Contributions

Khakoo Mal's contribution to this study was the concept and data collection. Imtiaz Hussain performed data curation and methodology. Tayab Din Memon performed the validation and paper writing. Dileep Kumar contributed to proofreading the paper and literature review. Bhawani Shankar Chowdhry plays the role of project director/administrator and puts this work in the right direction.

Conflict of Interest

There is no conflict of interest between all the authors.

Data Availability Statement

The testing data is available in this paper.

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