Real Time Detection of Low Adhesion in the Wheel/Rail Contact

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Abstract—**Condition monitoring of railway vehicles has in general been highlighted by the railway industry as an important technology that could be used to improve maintenance procedures or identify high risk vehicle running conditions without the use of cost prohibitive sensors.**

This paper presents on-going research into a particular system for detecting low adhesion during the normal operation of a railway vehicle. Here two difference methods are introduced. The first method is formulated around with the generation of a 'plan-view' linear model and the use of a Kalman-Bucy filter to estimate creep forces. The second method targets the assessment of relationships between vehicle dynamic responses to observe any behavioural differences as a result of an adhesion level change.

Both methods are concerned with investigating the dynamics of a Mk3 coach inclusive of a BR BT-10 bogie and a more modern class 158 vehicle. This research is supported by data generated by the multi-body simulation software 'VAMPIRE®' for realistic data inputs and the validation of results.

Keywords—**Railways, Vehicle Dynamics, Kalman Filters, Low Adhesion.**

I. INTRODUCTION

Low adhesion or the 'leaves on the line' problem is a large issue often misunderstood by the industry and general public alike. There is currently a lack of information about the changing picture of areas of low adhesion with respect to short term trends (over a daily period), and macro trends (across the seasons). The generally established methods of identifying these areas of low adhesion involve mapping activations of wheel slide and wheel slip protection events to track locations. This lack of knowledge of current adhesion conditions can cause over application of costly mitigation methods such as railhead cleaning.

The research described in this paper has been performed as part of a Rail Safety and Standards Board (RSSB) managed project T959. This follows on from the RSSB project T614 which investigated advanced methods of detecting areas of low adhesion in real time using 'modest cost' inertial sensors mounted to in service vehicles. It was proposed that the motions of a railway vehicle (in both lateral and yaw directions) vary as the adhesion conditions at the wheel/rail interface change [1]. Fundamentally, this means that if the changes in the running dynamics as a result of low adhesion can be observed and understood, the adhesion at all points across a rail network can be inferred, i.e. not only when slip/slide events are triggered.

A number of methods have been proposed to analyse data provided by inertial sensors mounted on the wheelsets, bogie and vehicle body. The main focus of the research has been developing a 'model-based' approach [2], [3] that uses a fundamental understanding of the physics of a rail vehicle to estimate wheel-rail creep forces that can't be measured directly. The application of this technique, including comparison work and analysis of data produced by VAMPIRE® railway simulation, will be presented in Section II.

The other stream of work highlighted in this paper is to directly analyse measured data in order to identify any features in the relationships between component dynamics as adhesion levels change. The current findings of this work are presented in section III.

II. MODEL-BASED ESTIMATOR

The technique of using a model based estimator has been developed and tested against linear suspension models generated in MATLAB/Simulink [1]. In this project the extension of the previous work is to apply this method against representative railway vehicle data. This data was supplied in the form of outputs taken from the simulations performed in the multi-bodied physics software package VAMPIRE®, generated for this project by DeltaRail. VAMPIRE® is a well validated specialist rail vehicle dynamics modelling software that simulates multi-degree of freedom/multi-bodied interactions of a railway vehicle. By using VAMPIRE® simulation data generated, it is possible to treat the data outputs as sensor readings in order to drive any linear models created. The outputs from these can then be compared against those that are captured directly from VAMPIRE®. This provides a suitable level of validation of the estimator technique to pave the way for real track testing.

This section gives a brief overview to the generation of a model based estimator and presents the current findings when this estimator is applied to VAMPIRE test data.

A. Methodology

The model-based estimator approach used previously is based around the well-known Kalman-Bucy filter [4]. In this case, a linearised model of the vehicle suspension system is used as the main component of the filter description in order to estimate the total lateral force and yaw moments at the wheel/rail interface [3]. It has been shown [5], [6] that the yaw and lateral dynamics contain the dominant characteristics of the motion and the other system dynamics can be neglected for the purposes of this study.

The first step of the process is to create and validate a representative simulation model of the system in question in

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MATLAB/Simulink. The linearised suspension component from the model can then be converted into state space form and used as the estimator model for the Kalman-Bucy filter.

B. *Model Development and Validation*

Models have been generated for comparison against two vehicles; a Mk3 coach based around the BR BT10 bogie and a class 158 vehicle - both of which are to be compared against simulation data generated in VAMPIRE®. The Mk3 coach has been selected for this study as there is an availability of this style of vehicle to use during a track test. A proof of concept of a successful system is required for this to go ahead. In preliminary tests, it has been found that the behaviour of the Mk3 is highly non-linear and causes some difficulty when trying to approximate these complex dynamics with a linear model. The geometry of the suspension is such that a linear plan view representation is difficult to validate successfully. As such, the class 158 vehicle was chosen as a test case due to its more linear characteristics and is more closely related to contemporary bogie design.

Figure 1 shows a plan view linear representation of the class 158 vehicle primary suspension. A linear model describing the dynamics is derived from here, mainly by considering the force/moment balance equations around the wheelset

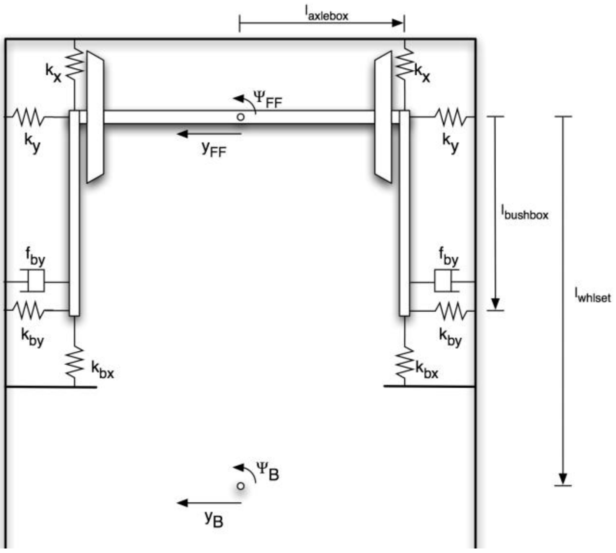

Fig 1. Plan-view linearised model of the Class 158 vehicle primary suspension system where:

y_{FF} – Wheelset lateral position
Ψ_{FF} – Wheelset yaw angle
Y_B – Wheelset lateral position
Ψ_B – Wheelset yaw angle
k_x – Primary Spring Stiffness (longitudinal)
k_y – Primary Spring Stiffness (latitudinal)
k_{bx} – Bush Spring Stiffness (longitudinal)
k_{by} – Bush Spring Stiffness (latitudinal)
f_{by} – Bush Spring Damping (latitudinal)
$l_{axlebox}$ – Axlebox semi-spacing
$l_{bushbox}$ – Bush box spacing from axlebox
l_{whlset} – Wheelset semi-spacing

For both vehicle cases, a linear simulation model considering the plan view movements only (yaw and lateral dynamics of each major vehicle component) was developed in Simulink. Each model generated contains a contact force description based on the works of Kalker [7] and Polach [8]. In addition, a Vampire test case for each vehicle was generated whereby the whole vehicle, containing a complete set of systems dynamics, simulated travel along a length of perfect track containing a 5mm lateral step after 1 second of travel. By applying the same track input to the Simulink simulation linear models, the dynamic response of the whole system can be compared over time with the Vampire data to assess for similarities and identify discrepancies.

A further, more useful test to validate the linear model is to check that the approximation of the component accelerations as a function of the vehicle dynamics are close to the equivalent recorded data in the VAMPIRE data. This initial test is designed to check the validity of the estimator as this relies on the accuracy of this function, which is essentially the mathematical description of the suspension. To perform this, the contact forces, bogie dynamics and wheelset dynamics recorded in a VAMPIRE simulation are input into the linear model which in turn derives the total wheelset lateral and yaw accelerations based on the approximated suspension loading calculated.

Figure 2 shows this so called ‘open loop’ response of the 158 class vehicle simulation models (Simulink and Vampire) in dry conditions.

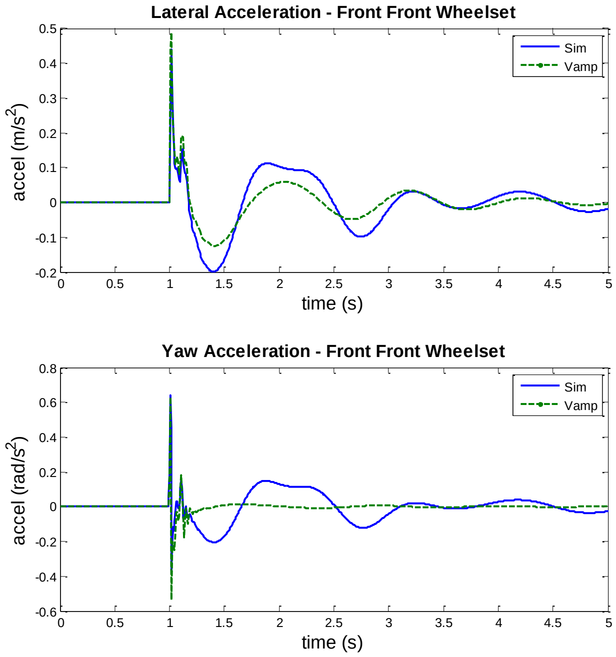

Fig 2. Figures showing the derived value of lateral and yaw acceleration overlaying the recorded values in VAMPIRE. These values are taken from the front wheelset of the front bogie – hence the ‘Front Front’ title.

In Figure 2, the solid blue lines show the resultant derived wheelset accelerations in the lateral and yaw directions from the linear Simulink model. The green dashed line shows the acceleration values recorded in VAMPIRE. It can be seen that the matches are close, but have a number of discrepancies. The differences between the models can be accounted for by:

- The 3D suspension geometry of Vampire compared to the 2D plan view assumption of the Simulink model.
- Linearisation of components in the Simulink model compared to non-linear components of the Vampire model.

- Simplification of some suspension components in the Simulink model.

In terms of application to a Kalman filter, the differences shown above are small enough to allow the linear model to form the estimator.

C. *Creep Force Estimation Technique*

The linear suspension model generated for the class 158 vehicle is converted into standard state space form given by equation 1 of the state equation.

$$\dot{x} = A_k x + B_k u \qquad (1)$$

Previous work has shown [9] that the Kalman-Bucy filter cannot distinguish between the creep forces and the gravitational stiffness are combined into one value. When choosing states, the total lateral force at each wheel interface is used as a state rather than the creep force and gravitational stiffness's individually.

In the case of the current model, the states within x are chosen as the positions and velocities of the wheelsets, in addition to the lateral forces mentioned above and the yaw creep moments. For the purposes of reducing the complexity of the model, the bogie positions and velocities are included in the u matrix. This means that the A_K and the B_K matrices describe the forces generated by the primary suspension due to the manipulations of the dynamics captured in the x and u matrices.

As described in detail by previous work done [1] the Kalman-Bucy filter is tuned primarily via the 'Q' matrix which identifies a degree of certainty with each of the state models. By setting the creep force state models as highly uncertain compared to the vehicle dynamics state models, the filter can be used to approximate the creep forces.

Figure 3 below shows an evaluation of this method at two different levels of adhesion; ideal dry conditions and low levels of adhesion. The actual values of friction defined for these levels were chosen to represent different levels of risk of the operation of the vehicle.

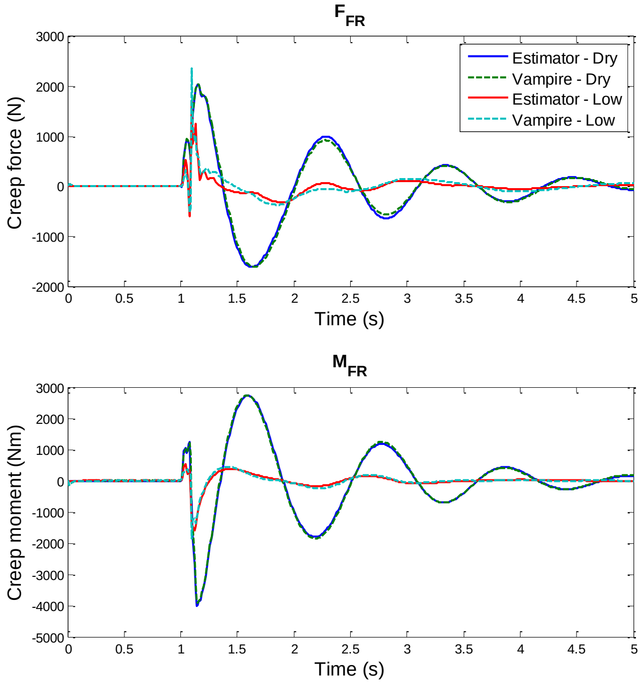

Fig 3. Figure showing the estimated lateral creep force and yaw creep moment overlaying the measured force and moment.

In each case, Vampire data was generated using the simulated section of track previously specified. This is then passed into the filter in order to represent sensor data measured in real time.

It can be seen that the model-based estimator provides a very good correlation to both the lateral forces and the creep moments at both adhesion levels. This shows us that although the linear approximations demonstrated in Figure 2 were not perfect, they were good enough to facilitate the implementation of the filter.

D. *Further Work*

Having attained a good approximation of creep forces and moments in this simple test case, the next step is to apply the estimator to a more realistic scenario. As part of the RSSB T959 project, DeltaRail have produced a number of synthesised runs of the class 158 vehicle using different track inputs and vehicle speeds. Having ascertained a good evaluation of the creep force, post processing methods require implementation in order to translate values of creep force to levels of adhesion.

In addition, having achieved a positive result on the class 158, attention will be turned back to the Mk3 bogie to attempt to ratify outstanding discrepancies between the models and apply the technique described in this section to form an estimator.

III. DIRECT DATA ANALYSIS

In parallel to the model based estimator work, investigations have been taking place directly analysing the data produced by the VAMPIRE simulation modelling at different adhesion levels. The aim here is to identify any features or relationships between measurable data that can be used to signify a change in adhesion levels without the need for the complexity of a derived model. After an initial search, the investigation followed two streams; relationships between leading and trailing bogie dynamics, and relationships between leading and trailing wheelset dynamics.

A. *Leading and Trailing Wheelsets*

Under high adhesion conditions it is known that during quasi-static curving the forces and relative movements of the leading wheelset are significantly larger than for the trailing wheelset [5]. It seems possible therefore that a comparison between leading and trailing wheelset dynamic data may provide a useful indication for low adhesion.

After an investigation on the data provided by DeltaRail for the Mk3 type vehicle, the most significant dynamic of interest was the yaw velocity comparison. Figure 4 shows the data recorded over a one second interval on a test track that contains lateral only disturbances. Figure 4a shows this test under dry conditions and Figure 4b shows this under very low conditions.

It can be seen that, at low adhesion conditions, the yaw velocity of the leading, trailing and bogie converge and begin to move more as a single unit. It is hypothesised that at low adhesion levels the track inputs are not of a significant magnitude to overcome the stiff wheelset-bogie yaw static connections and the secondary yaw friction levels inherent in parts of the Mk3 suspension design. The parts are therefore more likely to lock together and move as a unit, rather than display independent dynamics.

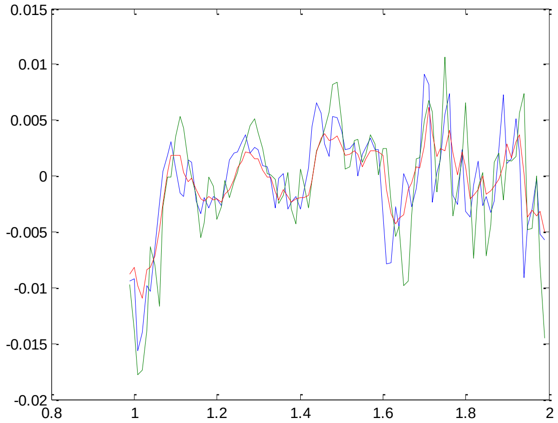

Fig4a. Graph showing leading, trailing and bogie yaw velocities in Dry adhesion conditions

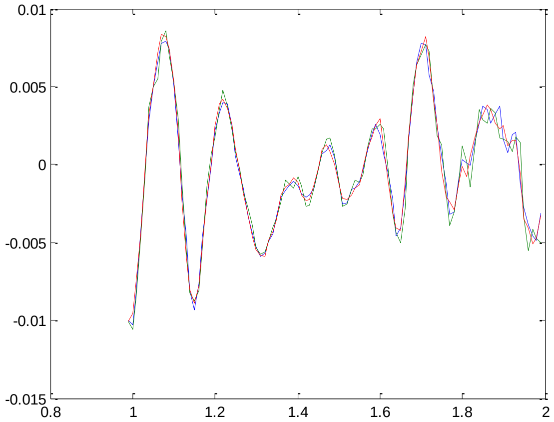

Fig 4b. Graph showing leading, trailing and bogie yaw velocities in Very Low adhesion conditions

This analysis showed initially promising results as there is a good match between the correlation of these dynamics and the level of adhesion. However, when an identical simulation test was performed with full track irregularities (i.e. vertical, cross level and gauge width irregularities), the results were less satisfactory.

This analysis shows that this does not yet appear to be a useful indicator for real-time adhesion detection. It has nevertheless revealed that the yaw motions of the two wheelsets in response to lateral irregularities become increasingly similar as adhesion levels reduce. To pursue this investigation further, appropriate normalisation or scaling factors are being studied to attempt to clarify the correlation. In addition, a similar investigation requires to be performed on the class 158 vehicle to see if similar traits are present and could be exploited to detect low adhesion conditions.

B. *Leading and Trailing Bogie Dynamics*

Similarly to the leading and trailing wheelset dynamics comparison, it was considered that a study to compareg leading and trailing bogie dynamics may yield a useful indicator for levels of adhesion. Once again, this study focused on the Mk3 bogie.

As with the study outlined in the previous section, this investigation began by comparing the correlation of all dynamic variables of the leading and trailing bogies. In addition, the variables were compared when taken at the same instant in time, and when the leading data is delayed so the comparisons are made as the bogies travel over the same piece of track. All the dynamics were considered at different adhesion levels to see if there were observable differences in correlation as the friction changes. It was found that the biggest change in correlation with adhesion was between the yaw angles of the two bogies. At high levels of adhesion, the correlation was found to be poor whereas at low levels of adhesion the correlation was high. As with the single bogie investigation, it is thought that this relationship is once again a result of the levels of static friction within the Mk3 suspension components.

In order to demonstrate this theory, the correlation of the leading and trailing bogies was measured through a number of different track and vehicle conditions. The data for these tests were taken from the datasets provided by DeltaRail's simulations of the Mk3 vehicle. Figure 4 below shows the implementation of the data processing scheme.

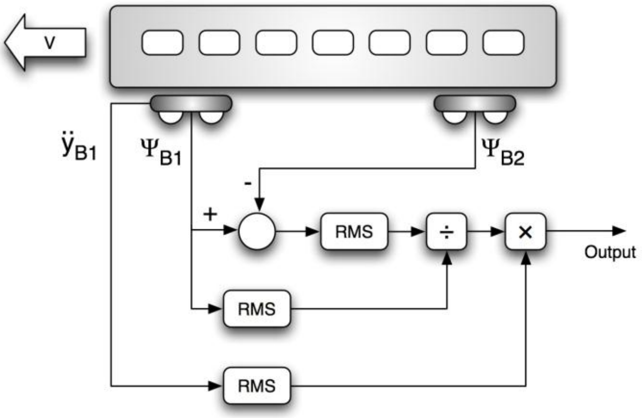

Fig 4. Diagram showing the data processing method in comparing leading and trailing bogie yaw angles where:

V – Vehicle Velocity,

$\ddot{y}_{B1}$ - Leading bogie lateral acceleration,

ψ_{B1} - Leading bogie yaw angle,

ψ_{B2} - Trailing bogie yaw angle

An RMS value is applied to the difference in yaw angle in order to apply some filtering to the noise. This is then scaled by the RMS value of the leading bogie and then again by the RMS of the lateral accelerations of the leading wheelset. The aim of the scaling is to normalise the output value for the variances in movement due to the size of track irregularity. Testing found that an RMS window of 600 samples (~10 seconds) gave a reasonable output.

Four test runs utilising this system are presented below. The conditions of these simulations are summarised in Table I. Each run consists of an instantaneous change in adhesion after 30 seconds in the direction highlighted in the third column of the table.

TABLE I
TEST RUNS FOR YAW ANGLE RMS COMPARISON

Run No.	Speed (kph)	Adhesion Change
1	200	High to V. Low
2	200	V. Low to High
3	100	High to V. Low
4	100	V. Low to High

Adhesion change: takes place after 30 seconds of transit in the direction highlighted

The resultant scaled RMS of the error between yaw angles derived from these test runs are shown below in Figure 5.

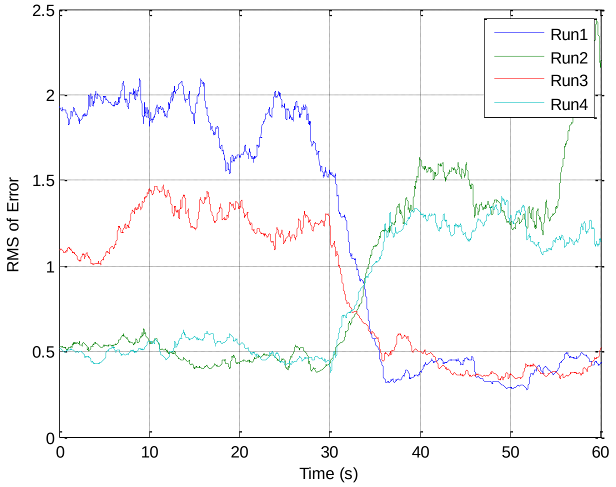

Fig 5. Figure showing the scaled RMS Error for 4 test runs.

Figure 5 shows that there is a distinct change of the RMS error value as adhesion levels change. Although this technique shows promise, there remains further work to confirm its viability as an adhesion detection method. This study has been applied on the Mk3 bogie model and may be attributed to the associated suspension features that are intrinsic to this bogie design. Initial studies on the class 158 vehicle show that this relationship of yaw angle is not as prominent as shown here for the Mk3.

Furthermore, although a distinct difference is observed between the two extreme conditions of high adhesion and very low adhesion, there is a requirement to detect between low and very low conditions. Although differences between these conditions can be observed within certain test runs, they are not as clear as the results shown above. These results may be improved by further normalisation with variables not yet considered.

IV. CONCLUSIONS

This paper has presented the current status of the work being undertaken to identify methods of real time low adhesion detection. The model based estimation technique is demonstrating good potential to provide accurate lateral force and yaw moment real time estimations on the class 158 vehicle.

Furthermore, the direct data analysis methods have provided some potentially useful markers for identifying low adhesion areas. As these methods approach the data directly, an accurate linear model of a complex, non-linear suspension model is not required. In the case of the Mk3 bogie where the suspension is troublesome to model linearly, refinement of these techniques could provide a solution where a model-based estimator may not.

The next stages of this work are to refine the methods presented in this paper. The model based estimator is to be applied to the real world scenarios of both the 158 and Mk3 test cases. The direct data methods are to be refined and tested on the class 158 test cases. Conclusions identified from this work will drive the direction taken with RSSB funded track testing that is hoped will take place in the New Year.

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