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Leaves on the Line: Low Adhesion Detection in Railways

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Abstract:
Regions of extreme low-adhesion between the wheel and rail can cause critical problems in traction and braking. This can manifest in operational issues such as signals being passed at danger, or pessimistic network wide responses to mitigate for localised issues. Poor traction conditions can be caused by oil contaminants, rain, ice, condensation of water droplets (micro-wetting) or leaves on the line, where compressed leaf contamination can cause a rapid decrease in adhesion. The complexity of the problem arises as a result of the inability to directly measure and monitor all the factors involved . There remains a lack of real-time information regarding the state and location of low-adhesion areas across rail networks.

On-board low adhesion detection technology installed to in-service vehicles is a suggested method to capture up-to-date adhesion information network wide and minimise significant disruptions and cancellations in railway schedules.

This paper extends a principle of a model-based estimation technique previously developed in straight track running for operating in a curving scenario. The vehicle model of focus here will be a simplified single-wheelset model attached to a suspended mass via representative stiffness and damping components. It is shown that in order for instantaneous creep forces to be estimated, the radius of the curve is required.

Keywords: Railways, Vehicle Dynamics, Kalman Filter, Low Adhesion, Creep Force, Curving.

1. INTRODUCTION

Rail networks are occasionally subject to regions of extreme low-adhesion between the wheel and rail. Deterioration in traction conditions can be a result of oil contaminants, rain, ice, condensation of water droplets (micro-wetting) or compressed leaf contamination - also commonly referred to as leaves on the line. Low adhesion can cause critical problems in traction and braking that can manifest in operational issues such as signals being passed at danger, or pessimistic network wide responses to mitigate for localised issues.

The complexity of the problem arises as a result of the inability to directly measure and monitor all the factors involved RRUKA (n.d.). There remains a lack of real-time information regarding the state and location of low-adhesion areas across rail networks. On-board low adhesion detection technology installed to in-service vehicles is a suggested method to capture up-to-date adhesion information network wide and minimise significant disruptions and cancellations in railway schedules Hubbard et al. (2013).

Previous studies of low adhesion at micro-slip using a tribometer train Fletcher (2012) suggested that the initial creep slope decreases for lower adhesion levels, in addition to the expected reduction of the saturation level. This means that variations in the adhesion level manifest in different dynamics of a railway vehicle in normal or unsaturated creep-force running. It has been shown that using this latest thinking in modelling, that real-time estimations for creep-force can be made across ranges of adhesion Hubbard et al. (2014).

A recent model-based estimation technique developed for creep force estimation relies on the inferring information from the changing yaw and lateral running dynamics of a wheelset and bogie as a result of varying adhesion levels Hubbard et al. (2013, 2014); Wickens (2003). The model used to form the estimator is based on a reduced-order linear suspension model, capturing the force and moments in only the lateral and yaw directions Garg and Dukkipati (1984). This technique has been validated against high-fidelity simulation data for normal running conditions (i.e. straight track, constant vehicle speed), but significant research is yet to be conducted where the vehicle is subject to transient conditions (i.e. traction / braking, curving). The current method has not been shown to estimate forces in these conditions. In curving, it is unable to account for the extra lateral forces in contact that occur due to the cant angle and centripetal force experienced.

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This paper details how the model-based, creep-force estimation technique can be expanded to a curving scenario. A single-wheelset vehicle model is used as a case study, by which a single wheelset is attached via a simple, linear primary-suspension to a suspended mass fixed in yaw. The vehicle model is subject to a series of simulations where the adhesion level between the wheel and the rail is varied in a curving scenario. The model makes use of a non-linear contact model in order to correctly represent an in-service wheel and rail profile. A Kalman-Bucy estimator Kalman (1960) is implemented to estimate contact forces as augmented states.

With the necessary inclusion of extra vehicle measurements and the extension of the linear suspension model from the straight-track scenario, it is shown that accurate creep force estimation can occur during a curve. The estimator is also shown to provide good results in the transition regions when entering and exiting the curve. In order to progress this research further, a method to infer adhesion from creep-force estimations within the curve is required. An accurate estimation of adhesion would require measurement of the track irregularity in order to extrapolate adhesion from creep force measurements. Furthermore, the test scenario should be extended to represent a half-vehicle model inclusive of a non-linear representation of both the primary and secondary suspension.

2. SIMULATION MODEL

The simulation model to be developed in order to test the creep force estimation methodology will be a simplified single-wheelset vehicle model. This incorporates linearised suspension components, but a non-linear contact model using the Polach contact law method Polach (2005) as opposed to the linear Kalker contact method Kalker (1967). This approach has been used in previous approaches for initial assessment of creep force estimation Ward et al. (2011c,b,a), but largely with a half-vehicle model.

2.1 Description of Contact Mechanics

The Polach contact method is used in this scenario as it adequately models the required non-linearities up to and beyond the point of saturation Polach (2005). The method was generated via a curve-fitting formula on experimental results as opposed to a complete first principle derivation. The principle is described by

$$F = \frac{2Q\mu}{\pi}\left(\frac{k_A\epsilon}{(1+k_A\epsilon)} + \arctan k_S\epsilon\right) \tag{1}$$

$$\epsilon = \frac{2}{3}\frac{C\pi a^2 b}{Q\mu}s \tag{2}$$

where F is the total creep force, μ is the coefficient of friction, s is the total creepage, Q is the wheel load, C is the creep coefficient term, a and b are the semi-axes of the elliptic contact patch and k_A and k_S are curve tuning parameters.

The total creepage and lateral an longitudinal forces (F_y and F_x) are given by

$$s = \sqrt{s_x^2 + s_y^2} \tag{3}$$

$$F_x = F\frac{s_x}{s} \tag{4}$$

$$F_y = F\frac{s_y}{s} \tag{5}$$

Although the spin term is small, it is added into the equations using a linear, Kalker approach as will be shown later. In the experimental results it was seen that the creep force began to decrease with increasing slip beyond the limit of adhesion. This variation in adhesions cofficient is modelled by

$$\mu = \mu_0\left[(1-A)e^{-B\omega} + A\right] \tag{6}$$

where ω is the the creep velocity and μ_0 is the limiting friction coefficient. A and B are curve tuning parameters.

In subsequent simulations, the level of adhesion is to be reduced in the wheel rail contact. This is facilitated by tuning the creep/creep force curve shape using the terms $\{k_A, k_S, \mu_0, A, B\}$. The adhesion levels selected correspond to risk levels associated with specific operating conditions. Four levels are selected; 'Dry', 'Wet', 'Low' and 'Very Low'. Dry and Wet are considered normal running conditions. Low and Very Low represent operationally restrictive conditions where defensive driving is required to mitigate the effects of low adhesion. Table 2 contains the value of parameters selected to represent the four different running conditions Charles et al. (2008).

Table 1. Margin settings

Parameter	Dry	Wet	Low	Very Low
k_A	1.00	1.00	0.60	0.30
k_S	1.00	1.00	0.20	0.10
μ_0	0.55	0.30	0.06	0.03
A	0.40	0.40	0.40	0.40
B	0.60	0.20	0.20	0.10

Table 2. Contact parameters used to define different running conditions Charles et al. (2008)

The formulas for creep are derived by considering the relative linear and angular motions between the wheel and rail. By defining vectors describing the relative positions of the wheels and the rail, a derivation can be followed Garg and Dukkipati (1984) to yield equations 7 - 12 that describe the creepage.

Left wheel:

$$s_{xL} = \frac{1}{V}\left\{V\left(1 + \frac{a}{R} - \frac{r_L}{r_0}\right) - a\dot{\psi}\right\} \tag{7}$$

$$s_{yL} = \frac{1}{V}\left\{\dot{y} - V\psi + r_L\phi\right\} \tag{8}$$

$$s_{spin} = \frac{1}{V}\left\{-\Omega\delta_L + \left(\dot{\psi} - \frac{V}{R}\right)\right\} \tag{9}$$

Right wheel:

$$s_{xR} = \frac{1}{V}\left\{V\left(1 + \frac{a}{R} - \frac{r_R}{r_0}\right) + a\dot{\psi}\right\} \tag{10}$$