Fuzzy logic creep control for a 2D locomotive dynamic model under transient wheel-rail contact conditions

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Abstract

In recent decades, advanced power-electronics-based control techniques have been widely used to electric drives for the traction of modern locomotives. However, the dynamic response of such locomotives under transient conditions due to external perturbations has not been fully investigated. In this work, an integrated dynamic model for a typical Co-Co locomotive/track system is developed to provide predictive simulations of the motion and forces transmitted throughout the whole locomotive dynamic system. The model integrates a 2D longitudinal-vertical locomotive structural vibration model, wheel/rail contact mechanics using Polach's creep force model, a simplified dynamic traction model and a fuzzy logic creep controller to simulate the transient response to a change in friction conditions. It is found that the proposed fuzzy logic controller has the advantage over a PI controller in terms of achieving higher tractive force under transient contact conditions.
Keywords: locomotive creep control, fuzzy logic, transient contact conditions.

1 Introduction

The progressive adoption of high traction motors and control techniques based on power electronics has brought great benefits to the rail industry due to its high power capacity and efficiency. Despite all the advantages, concerns arise as to

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the effects of operating at maximum adhesion and the possible impact of dynamic oscillations and resultant traction to the rail tracks. An electric locomotive is a complex system containing several nonlinear dynamic components coupled together when the locomotive operates. Its traction control performance and dynamic impact on the rail tracks are typically assessed under specific steady state conditions. However, the natural perturbations in friction/lubrication, wheel/rail profiles, track curvature, vehicle/track dynamics, wheel/track imperfections etc. are not comprehensively investigated yet. Among those perturbations, the transient changes in friction or lubrication can cause sudden changes of creep and often leads to over/under traction/braking. In order to investigate this issue, a predictive locomotive dynamic model combining crucial dynamic components such as locomotive rigid body dynamics, contact dynamics and electric drive and control is needed.

Locomotive traction simulations have been investigated by several researchers. A simulation package for simulation of rail vehicle dynamics has been developed in Matlab environment by Chudzikiewicz [1] for Poland railway specifications. Traction simulation considering bogie vibration has been provided by Shimizu *et al.* [2] and a disturbance observer based anti-slip controller is also proposed. Spiryagin *et al.* [3] employed co-simulation approach with the Gensys multibody code and Simulink to investigate the heavy haul train traction dynamics. Fleischer [4] proposed a modal state controller to reduce drive train oscillation during the traction simulation. Bakhvalov *et al.* [5] combined electrical and mechanical processes for locomotive traction simulation. Senini *et al.* [6] has also performed some locomotive traction and simulation on electric drive level. These works however, haven't focused investigation on the effect of transient contact conditions on the locomotive dynamic response. In this work, we focus on longitudinal and vertical dynamics on tangent tracks as it is the most important part of locomotive dynamics closely related with traction/braking effort, passenger comfort and energy management [7]. Newton-Euler method [8, 9] is used to obtain the motion equations of the locomotive model. For the contact mechanics, Polach's adhesion model [10] is adopted as it has been verified to be effective for both small and large values of longitudinal wheel-rail creep as well as the decreasing part of creep-force function exceeding the adhesion limit [11]. Modern development of mechatronics systems has improved rail vehicle operation under various conditions. The traction control system, also known as an adhesion or anti-slip control system is essential for the operational efficiency and reliability in these systems. A pattern-based slip control method has been applied and modified by Doh-Young *et al.* [12]. Anti-slip control based on a disturbance observer was proposed by Ohishi *et al.* [13]. Yasuoka *et al.* [14] proposed slip control method involving bogie oscillation suppression. Fuzzy logic traction control has been investigated by Research and Development sectors of locomotive manufacturers such as Siemens [15] and General Motor Cooperation [16]. The real life experiments of fuzzy logic traction/braking control have mainly been carried out in automobile platform or in-lab environment [17–19]. A number of researches have been performed on fuzzy logic aiming for improvement of motor traction control performance based on industrial programmable logic controller (PLC) [20–23] and other hardware platforms [24]. All these methods claim the effectiveness of their proposed creep/traction controller; however, these conclusions were not validated on a comprehensive locomotive dynamic model.

In this paper, a full scale locomotive dynamic model with a fuzzy logic creep controller combining all crucial dynamic components is developed and implemented using Matlab/Simulink to investigate creep and dynamic oscillation. In addition, a traction control system is proposed and embedded into the dynamic model to prevent inefficient traction caused by perturbations.

2 Modelling details

The locomotive model is comprised of three major dynamic components: locomotive longitudinal-vertical-pitching dynamics, electric drive/control dynamics, and contact mechanics. The structure of the model is shown in Figure 1. A dynamics model of the mechanical system of an electric locomotive based on the Newton-Euler method is developed. The wheel-rail contact in this model is based on Polach's model. And a simplified electric drive model with a basic creep controller is proposed and integrated into the electric drive/control dynamics block in this model.

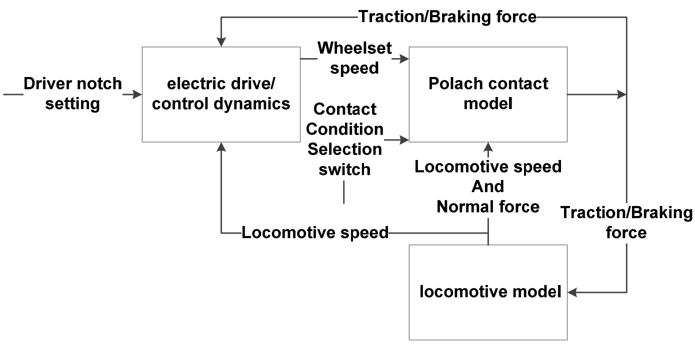

Figure 1: Overall model structure of a locomotive.

The model may be described as a feedback system. The electric drive and control system provides a torque acting on the motor shaft in the locomotive model. Torque also results from the longitudinal force due to the interaction between wheel-rail track contact mechanics. The resultant creep changes the longitudinal tractive force calculated using the Polach model, and the tractive force acts on the locomotive dynamic model and changes the displacements and velocities of the rigid bodies. Each of those components is detailed in the following sections.

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2.1 Locomotive 2D dynamic model

The locomotive dynamic model is illustrated in Figure 2. In this model longitudinal, vertical and pitching dynamics are taken into consideration. The simplified Co-Co locomotive has two bogies. Each bogie has three wheelsets attached. Key parameters including geometry, degrees of freedom etc., are marked in Figure 2.

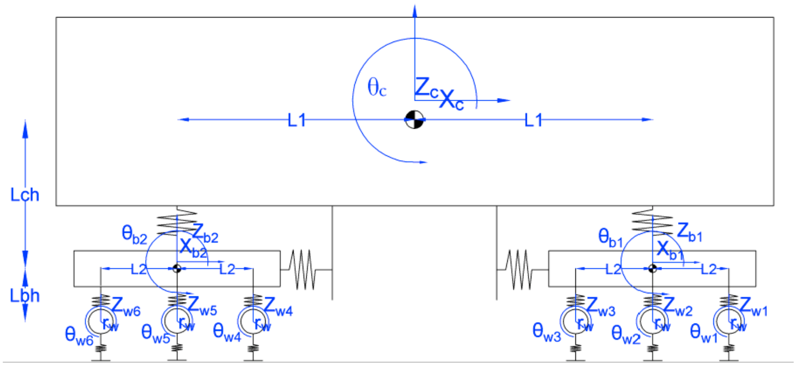

Figure 2: Diagram of simplified locomotive multibody structure.

This simplified dynamic model has 21 degrees of freedom (DOF), including 9 DOF on the longitudinal, vertical and pitching motion of locomotive body and two bogies, and 12 DOF on vertical and rotating motion of six wheelsets. The system variables are expressed as a vector containing 42 entries, representing the relative displacements and velocities between different nodes as

$$X = [Z \quad \dot{Z}]^T, \quad Z = \left[Z_{carbody} \quad Z_{bogie1} \quad Z_{bogie2} \quad Z_{axles}\right]^T \tag{1}$$

in which $Z_{carbody} = [x_c, z_c, \theta_c]^T$ is a 3×1 vector representing the locomotive body longitudinal, vertical and pitching motion from the static positions, $Z_{bogie1} = [x_{b1}, z_{b1}, \theta_{b1}]^T$ and $Z_{bogie2} = [x_{b2}, z_{b2}, \theta_{b2}]^T$ are both 3×1 vectors representing longitudinal, vertical and pitching motion of front and rear bogie separately, and $Z_{axles} = [z_{w1}, \theta_{w1}, z_{w2}, \theta_{w2}, \ldots, z_{w6}, \theta_{w6}]^T$ is a 12×1vector representing the vertical and rotating motion of wheelset 1–6. The state space representation of the simplified dynamics can be expressed as:

$$\begin{aligned} \dot{X} &= A \cdot X + B \cdot u \\ Y &= C \cdot X + D \cdot u \end{aligned}, \quad A = \begin{bmatrix} \Theta & \mathrm{I} \\ M^{-1}K & M^{-1}C \end{bmatrix} \tag{2}$$

where u is the longitudinal tractive force resulted from the interaction between the wheelsets and rail tracks, Y is a vector of displacement or velocity of each

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node from its static position, Θ is a zero matrix, I is an identity matrix of certain dimensions, and M is the diagonal mass and moment of inertia matrix in the form of

$$M = diag(M_c, M_c, I_c, M_t, M_t, I_t, M_t, M_t, I_t, M_w, I_w, M_w, I_w, M_w, I_w, M_w, I_w, M_w, I_w, M_w, I_w) \quad (3)$$

2.2 Contact mechanics

The Polach model [10] is employed in the contact mechanics component to determine the longitudinal tractive force resulted from the interaction between the wheelsets and rail tracks. In the model, the longitudinal tractive force can be expressed as

$$F = \frac{2Q\mu}{\pi}\left(\frac{k_A\varepsilon}{1+(k_A\varepsilon)^2} + \arctan\left(k_s\varepsilon\right)\right) \quad (4)$$

where $\mu = \mu_0\left[\left(1-A\right)e^{-B\omega} + A\right]$, $A = \dfrac{\mu_\infty}{\mu_0}$, $\varepsilon = \varepsilon_x = \dfrac{1}{4}\dfrac{G\pi abc_{11}}{Q\mu}s_x$, $s_x = \dfrac{w_x}{V}$

for longitudinal direction. Parameters are defined as in [10]: F is tractive force, Q is normal wheel load, μ is the coefficient of friction, k_A is the reduction factor in the area of adhesion, k_s is the reduction factor in the area of slip, ε is the gradient of the tangential stress in the area of adhesion, ε_x is the gradient of the tangential stress in the longitudinal direction, μ_0 is the maximum friction coefficient at zero slip velocity, μ_0 is the friction coefficient at infinite slip velocity, A is the ratio of friction coefficients, B is the coefficient of exponential friction decrease, ω is the total creep (slip) velocity, ω_x is the creep (slip) velocity in the longitudinal direction, G is the shear modulus, a,b are half-axes of the contact ellipse, c_{11} is a coefficient from Kalker's linear theory and V is vehicle speed.

Parameters describing dry and wet contact conditions have been adopted from Polach's work [10] as below:

Table 1: Parameters for different contact conditions.

Conditions parameters	Dry	Wet
k_A	1	0.3
k_S	0.3	0.75
μ_0	0.55	0.3
A	0.4	0.4
B	0.25	0.09

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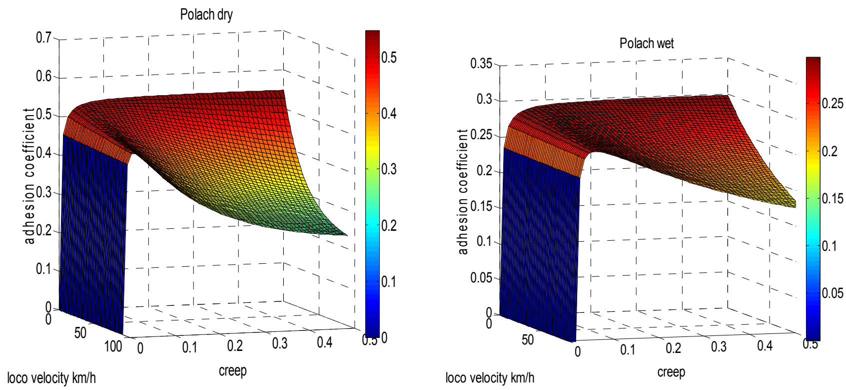
The resulting creep-adhesion characteristics under dry and wet conditions are as in figure 3 a) and b) respectively,



a) b)

Figure 3: a) Creep, speed and adhesion coefficient relation under dry contact condition; b) Creep, speed and adhesion coefficient relation under wet contact condition.

2.3 Simplified motor dynamic modelling

A simple motor dynamic model characterizing the electromagnetic torque T_e, mechanical loading T_l, the equivalent moment of inertia of the axles with the motor rotor J_m and the angular acceleration of axles $\dot{\omega}_w$ can be written as [25]

$$J_m \dot{\omega}_w = T_m - T_l \tag{5}$$

3 Proposed control system

The proposed adhesion control system utilizes the method described in [26] to determine the locomotive speed which will be used to calculate the creep values of each axle. And an adhesion force coefficient observer proposed in [13] is adopted to generate the ‘optimum’ reference motor torque signal. The control system diagram is as shown in figure 4.

A fuzzy logic creep controller is adopted in this work as its advantage of giving strong self-adaptive and robust performance without the need of accurate mathematical model [27]. The proposed fuzzy logic controller uses the information of differentiation of each axle’s creep of and the differentiation of each axle’s adhesion coefficient, which is estimated from the change in vehicle acceleration over one sample period as proposed in [28]. Each of the fuzzy inputs of derivative of creep and derivative of adhesion coefficient are expressed by

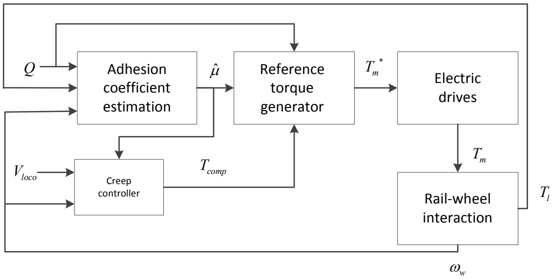


Figure 4: Adhesion control diagram.

5 fuzzy membership functions, e.g. positive big (Pb),positive small (Ps), zero (0), negative small (Ns) and negative big (Nb). The output of the fuzzy logic controller is torque compensation command to each of the motors, either to increase or reduce the electromagnetic torque acting on the motors within the range of traction limit.
Controller output:

$$T_m^*(N) = T_m^*(N-1) + T_{comp}(N) \tag{6}$$

The membership functions and control rules are in Table 2 and Figure 5 below.

Table 2: Fuzzy rule table.

Derivative of creep ($\dot{s}$)	**Derivative of adhesion coefficient ($\dot{\mu}$)**				
	Pb	***Ps***	***0***	***Ns***	***Nb***
Pb	Pb	Ps	Ns	Ns	Nb
Ps	Ps	Ps	0	Nb	Nb
0	Ps	0	0	Ps	Ps
Ns	Ns	Ns	Ps	Ps	Pb
Nb	Ns	Ns	Ps	Ps	Pb

The fuzzy rules are designed based on [28], i.e. dividing the creep-adhesion coefficient curve into four different sessions according to the value of $\dot{s}$ and $\dot{\mu}$ (1–4 representing sessions of dry contact condition curve; 1*–4* representing sessions of wet contact condition curve) (as shown in Figure 6):

1 and 1*: $\dot{s}$ is positive and $\dot{\mu}$ is positive

2 and 2*: $\dot{s}$ is positive and $\dot{\mu}$ is negative

3 and 3*: $\dot{s}$ is negative and $\dot{\mu}$ is positive

4 and 4*: $\dot{s}$ is negative and $\dot{\mu}$ is negative

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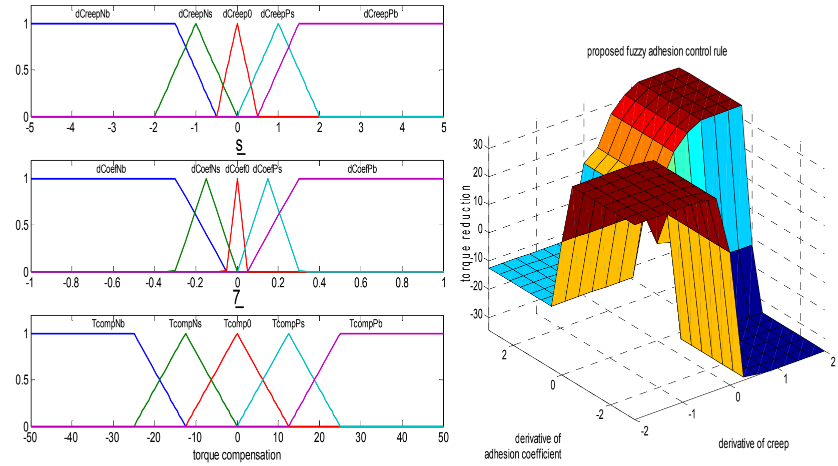


(a) (b)

Figure 5: (a) Membership functions of inputs and output; (b) fuzzy logic 3D input-output characteristics.

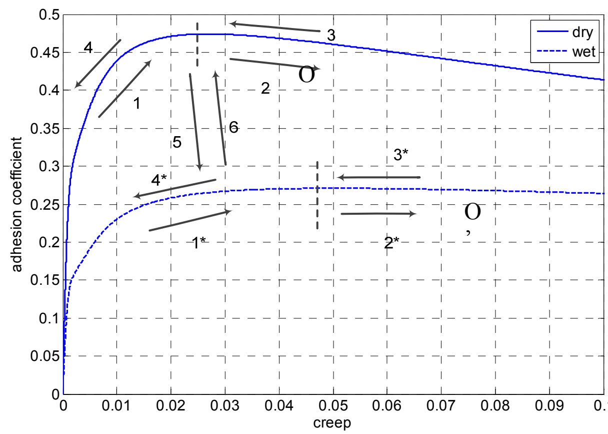


Figure 6: Illustrative graph for the fuzzy rules.

Moreover, transient condition caused by the change of wheel-rail contact condition is also taken into consideration. Thus two additional sessions have been added:

5: Transient from high curve to low curve- $\dot{s}$ positive and $\dot{\mu}$ negative very large

6: Transient from low curve to high curve- $\dot{s}$ negative and $\dot{\mu}$ positive very large

The principle of the logic is to maintain the adhesion coefficient at maximum value O for dry contact condition or O' for wet contact condition, by reducing the torque command when creep value is on the right hand side of maximum values and increasing the torque command when on the left hand side of maximum values.

4 Results

Results of transient locomotive response with proposed fuzzy logic controller are illustrated, including creep and tractive force. Initial operation speed was set at 10 km/h. Transient contact conditions are assumed to happen at 11km/h, from dry contact condition to wet condition, and change back from wet to dry contact condition at 12.5 km/h.

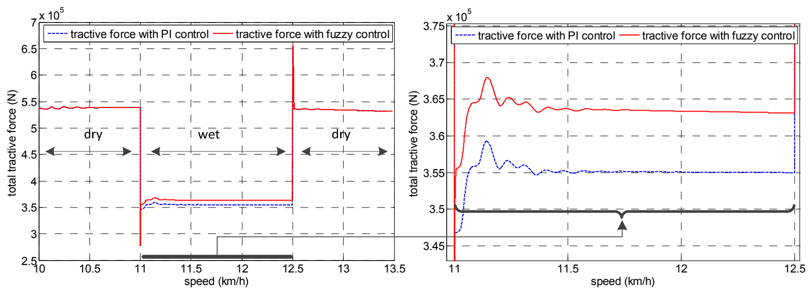
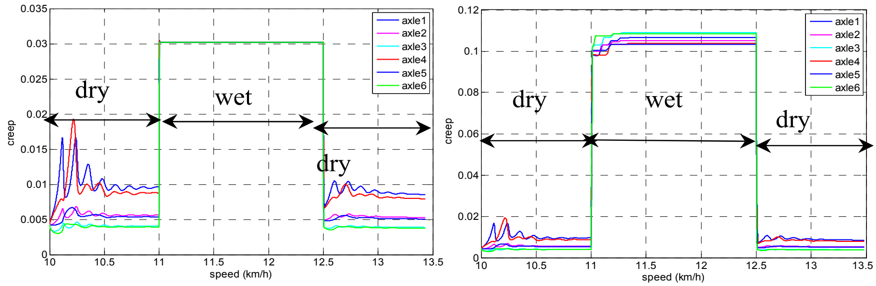


Figure 7: Comparison of total tractive force with PI and fuzzy controller (left); magnification of tractive force comparison under wet contact condition (right).

It can be seen from Figure 7 that the tractive force with PI and fuzzy controller under dry contact condition is similar, while then the fuzzy controller can reach higher tractive force than that with PI controller under wet contact condition. This can be explained as follow. As the threshold of the PI controller is chosen such that it can reach the maximum tractive force under dry contact condition near the simulation speed, the tractive force with controller are close to each other, both around the maximum tractive force the system can reach at the same speed. However, as the threshold of the PI controller is constant, it will not be able to adjust the control level according to the change of contact conditions and/or operating speed. On the other hand, the fuzzy controller search for maximum tractive force with information of $\dot{s}$ and $\dot{\mu}$. This causes higher tractive force under wet contact condition with fuzzy controller than that with PI controller.

In Figure 8(a), after the contact condition changes from dry condition to wet condition, the creep values have been limited at 0.03, as the pre-set threshold of the PI controller, whereas the creep values of the system with fuzzy logic are higher as in Figure 8(b), as the fuzzy controller adjusts the control effort according to the operation condition and intends to reach maximum tractive force available.



(a) (b)

Figure 8: Comparison of creep response with PI control (a) and with fuzzy logic control (b).

5 Conclusions

External perturbations such as the change of rail-wheel contact conditions often cause undesirable locomotive dynamic responses. In this paper, the locomotive dynamic responses under transient contact conditions with PI and fuzzy logic creep controller have been simulated with an integrated 2D Co-Co locomotive/track dynamic model. The comparison of the creep and total tractive force shows the advantage of proposed fuzzy logic controller over PI controller in term of realizing higher tractive force under the change of contact conditions. While both controllers can limit the creep under a certain level, simulation results show that the fuzzy controller can reach higher total tractive force than that with a constant threshold PI controller under wet contact condition thanks to its ability to search for the maximum achievable force according to different contact conditions.

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