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## Contribution to the certification of a WSP device in a HIL environment through a new adhesion recovery model

Moncef TOUMI<sup>1</sup>, Michel SEBES<sup>2</sup>, Karl LADEN<sup>3</sup>, Hugues CHOLLET<sup>2</sup>, Mohammed BOUALLAGA<sup>1</sup>

<sup>1</sup>RAILENIUM, Famars, France

<sup>2</sup>IFSTTAR, Champs sur Marne, France

<sup>3</sup>Bombardier Transportation, Crespin, France

Corresponding Author: Moncef TOUMI (Moncef.toumi@railenium.eu)

### Abstract

Assessing the dynamic behavior of railways vehicle by numerical simulations requires a consistent wheel rail contact model that gives accurate normal and tangential forces. The current contact theories implemented on most multi-body systems (MBS) consider the adhesion coefficient as constant in time during the simulation. This means that the wheel and the rail cleaning due to axles sliding and leading to regenerate adhesion is generally neglected. However, such an assumption is invalid for many applications especially for traction and braking where longitudinal creepage could be relatively high leading to important effect of cleaning and high adhesion recovery.

In this paper, the frictional contact model of the multibody software VOCO is extended to take into account the adhesion recovery due to axles sliding in a braking context. The adhesion time-dependent model is based on the calculation of the power dissipated by friction at the wheel-rail contact level and was validated by comparisons with measurements provided from on-track braking tests performed with the Regio 2N ONO vehicle. The model has improved predictions of braking distance, axle speeds and train deceleration when performing braking simulations. A virtual Wheel Slide Protection (WSP) system that co-simulates with VOCO the dynamic response of the vehicle inside an exchange procedure was used in this work. The exchange procedure was designed to run in real-time in order to be further implemented inside a Hardware In the Loop (HIL) architecture with a real WSP device.

Keywords: Adhesion recovery, wheel-rail contact, braking, multi-body system

### 1. Introduction

On-track braking tests are required in railways in order to certificate a WSP device or to homologate a new vehicle. The high costs and the organizational challenges (network availability) of these tests lead WSP and train manufacturers to search alternative ways to reduce at maximum their number in order to shorten time to market. UIC leaflet [1] and EN [2] standards allow to partially replace on-track braking tests by on-bench tests composed by a combination between test rig use and numerical simulations. The procedure enables to test full WSP components (speed sensors, dump valve...) using a simulator to reproduce the vehicle dynamics behavior that needs to exchange information in real-time with the WSP device inside a HIL environment. This alternative is particularly interesting for manufacturers as it not only allows to determine the braking performances of the train but also opens the door to many other uses like optimizing the WSP parameters and the testing process before on-track tests or like helping engineers to find the origin of the problem after an incident. The test bench allows also simulating all the cases that are difficult to reproduce by on-track tests or to do some non-regression tests under the same conditions which is particularly interesting to demonstrate that the software evolutions has no influence on the performances.

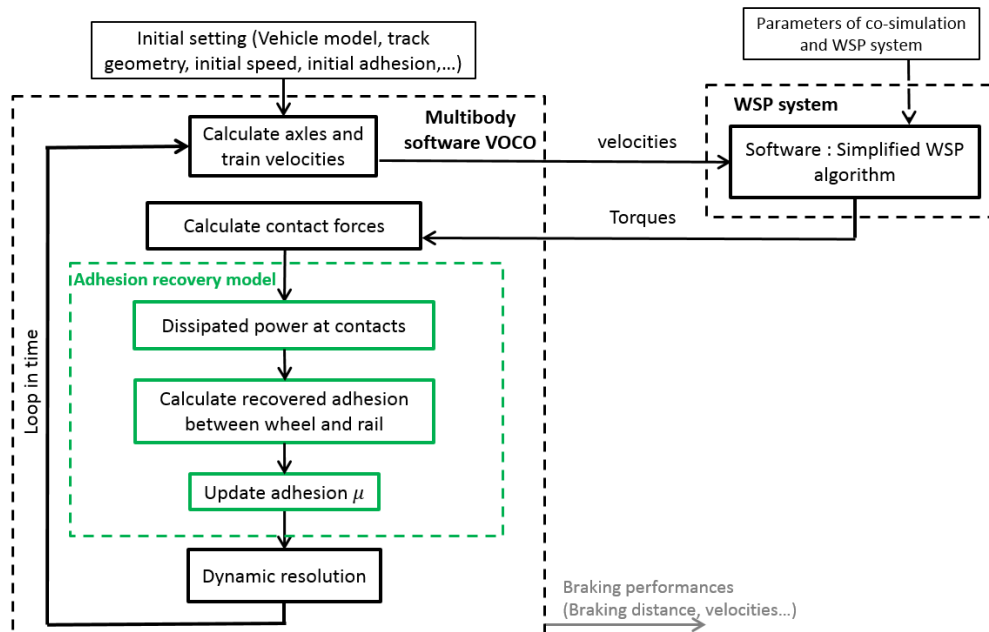
Wheel-rail contact and adhesion coefficient need to be correctly modeled by the simulator in order to get accurate normal and tangential forces. In order to comply with Multi-Body Systems (MBS) requirements in terms of computing time, wheel-rail contact models usually assume a constant friction throughout the simulation. However, when high tractive or braking forces are concerned, modeling adhesion becomes very complicated as it may depend in reality on many aspects like sliding, temperature, train speed, axle load etc. Many authors studied the parameters that could influence the adhesion coefficient [3] [4] and some of them proposed numerical models compliant with MBS. Polach

[5] first introduced an adhesion model depending on slide and velocity fitting with adhesion measurements in dry and wet conditions. Other authors [6] adapted the original FASTSIM algorithm by Kalker [7] in order to take in account a slide-dependent friction. In addition experiments [8] show that adhesion may recover with time due to a cleaning of contaminated surfaces. Allotta et al. [9] developed a model enabling to take in account this cleaning effect: this model is based on an interpolation between 2 sets of parameters of Polach's model [5] associated respectively to wet (or contaminated) and dry (or recovered) conditions. This interpolation depends on the dissipated energy for unit of distance. In this paper, a similar adhesion model is proposed taking in particular in account the cleaning effect of the preceding wheels of a trainset. This model has been implemented in the MBS VOCO and benchmarked by comparison with on-track tests on a Regio 2N trainset. The methodology is described in section 2. Simulation results are confronted with measurement in section 3.

## 2. Methodology

### 2.1 General procedure

Figure 1 describes the general procedure used in this work to simulate train braking. The big left dotted box represents the essential steps followed in the MBS VOCO to simulate the dynamic behavior of the full train and the wheel-rail contact. The adhesion recovery represented by the green dotted box is fully implemented in VOCO. Details of this model will be presented in section 2.4. The dotted box on the right represents the WSP system that analyzes all axle speeds given by VOCO and then send back the appropriate braking efforts or torques that should be applied to the axles. At this stage of the research, the WSP system is virtually simulated by a simplified algorithm that will be described in the following section.



**Fig. 1: General architecture of the exchange procedure between VOCO and the WSP system.**

Axle positions and velocities are updated in VOCO at every time step  $\Delta t$  but velocities and torques are exchanged between VOCO and the WSP system only every time period  $\Delta T_e$  which correspond to the exchange frequency.

Despite that it is not mandatory to simulate braking in real-time when two softwares are involved in the co-simulation, the exchange has been designed to respect this criteria. It has been verified in this work that real-time was well respected. Thus, replacing the simplified algorithm by the full WSP hardware device should be easily done in our future work. At the end of the co-simulation, the MBS VOCO assesses the braking performances of the train to be compared with measurements.

## 2.2 Simplified WSP algorithm

To simulate braking, it is possible in VOCO to control braking torques complying with a specified speed law. However, the speed law needs to be known a priori and the WSP logic in this case is absent. A simplified WSP algorithm was introduced in VOCO in this work and allows to overcome those limitations. Using this simplified algorithm instead of the real WSP device has many benefits for this first step of the work. First, it is easier to implement in the general architecture described in Figure 1 and it allows to verify that the exchange procedure works well before using it in the HIL environment. Second, it allows to better study the contribution of the adhesion recovery model on improving the braking simulation. The simplified WSP algorithm described in Table 1 has 3 different states (fill, hold and vent) that determine its operating modes. Those modes depend on four levels that vary from  $s1=5\%$  to  $s4=25\%$ .

**Table 1: Different states of the simplified WSP algorithm.**

<i>Start : GOTO State 1</i>		
1	Fill	IF (slip > $s2=10\%$ ) THEN GOTO State 2
2	Hold	IF (slip < $s1=5\%$ ) THEN GOTO State 1 IF (slip > $s4=25\%$ ) THEN GOTO State 3
3	Vent	IF (slip < $s3=20\%$ ) THEN GOTO State 2

The slip is calculated using the following expression:

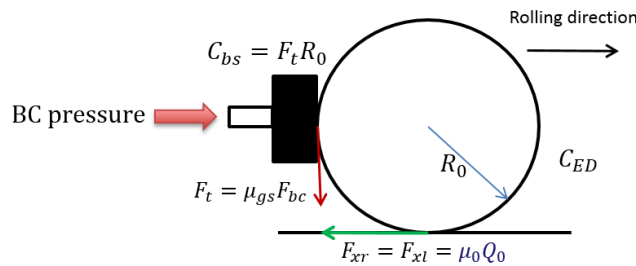
$$\text{slip} = \frac{\text{Vehicle velocity} - \text{axle velocity}}{\text{Vehicle velocity}} \times 100 \quad (1)$$

The fill and the vent processes are determined by the following expressions:

$$\text{Torque increase (Fill): } C = C_{lim} (1 - e^{-\frac{t}{T_{oi}}})$$

$$\text{Torque decrease (Vent): } C = e^{-\frac{t}{T_{od}}}$$

Where  $T_{oi}$  and  $T_{od}$  are time constants and  $C_{lim}$  is the maximum total torque reached during the fill process which includes for a driven axle (Figure 2) the torque due to the brake shoes  $C_{bs}$  and the torque due to the electrodynamic brake  $C_{ED}$ .



**Fig. 2: Forces applied to a driven axle.**

## 2.3 Initial adhesion coefficient

The adhesion model that will be presented in the following section allows to take into account adhesion recovery due to axles sliding and to better describe rail cleaning during braking. Thus, the final state of adhesion is a result given at the end of the simulation that considers all axles contribution to this rail cleaning process. However, the initial state of adhesion  $\mu_0$  is not known and needs to be estimated as it is an input of the model.

The method used to calculate  $\mu_0$  in this paper is based on applying laws of motion to the first sliding axle. By considering the rolling diameter  $R_0$  as the same for the right and left wheels, it gives:

$$J_a \dot{\omega}_a = C_{ED} + C_{bs} - R_0(F_{xr} + F_{xl}) \quad (2)$$

With:

$C_{ED}$  : Torque due to electrodynamic brake given from measurement

$C_{bs}$  : Torque due to brake shoe given from measurement

$\dot{\omega}_a = \frac{d\omega_a}{dt}$  : Deceleration of sliding axle given from measurement

$J_a$  : Inertial mass of sliding axle

$F_{xr}, F_{xl}$  : Right and left longitudinal contact forces

When the following assumptions are considered:

- The load per wheel  $Q_0$  is static and equal at right and left side of the axle
- Adhesion coefficient  $\mu_0$  is the same for right and the left rails
- Axle is sliding over the rail which means that  $F_{xr} = F_{xl} = \mu_0 Q_0$

The final expression of  $\mu_0$  could be deduced from (2) as:

$$\mu_0 = \frac{(C_{ED} + C_{bs} - J_a \dot{\omega}_a)}{2 \times R_0 Q_0} \quad (3)$$

## 2.4 Adhesion recovery model

As most MBS, VOCO allows to use an adhesion coefficient that varies in distance but not in time. The variation of adhesion in time means here its dependency to events that contribute to the rail cleaning process at a given position  $x$  like axles sliding, wheels self-cleaning due to contact with rail, wheels cleaning due to brake shoes for a driven axle or even the activation of the electromagnetic brake (EMB) applied directly to the rail during emergency braking.

To better simulate what is actually happening in situ during braking, these events need to be modeled. In this paper, we focus on modeling the rail cleaning due to axles sliding. An algorithm that allows to regenerate adhesion using an energetic approach was introduced in VOCO. Its principle is simple: adhesion recovery is a function of the power  $P$  dissipated by friction at the wheel-rail contact level that is given by the following expression:

$$P(x, \tau) = (F_x v_x + F_y v_y) \cdot V \quad (4)$$

Where  $F_x, F_y$  are longitudinal and the lateral contact forces;  $v_x, v_y$  are longitudinal and lateral creepages and  $V$  is the train speed. This power  $P$  is equal to the energy dissipated at the contact for unit of distance introduced by Allotta et al [9] times the train speed.

This adhesion coefficient  $\mu(x, t)$  is then calculated using the following expression:

$$\mu(x, t) = \mu_{max} + (\mu_0(x) - \mu_{max}) e^{-\frac{\sum_{\tau=0}^t P(x, \tau)}{P_0}} \quad (5)$$

Where  $\mu_0(x)$  is the initial adhesion coefficient seen by the first axle and calculated as described in the previous section;  $\mu_{max}$  is the maximum reachable adhesion;  $P_0$  is a constant of the model expressed in Watts that quantify the degree of regeneration.

The rail cleaning due to axles sliding at a position  $x$  of the rail is taken into account in the expression (5) by summing the power dissipated by friction from all preceding axles.

The expression (5) enables to enhance the model in case of a low initial adhesion (between 0.05 and 0.08 according to the EN 15595 standard [2] or between 0.03 and 0.08 according to the UIC 541-05 [1]) which corresponds in practice to natural wet conditions (rainy) or artificial wet conditions (sprayed rail). In the presence of low adhesion, the first axles of the train slide a lot and thus dissipate much energy which results in the liquid film ejection. Adhesion is then restored until a sufficient high limit is reached that allows the following axles to slide less and therefore slow down the train better.

The adhesion recovery model requires to be validated by comparison with measurements from braking tests. An example of this comparison is presented in the following section.

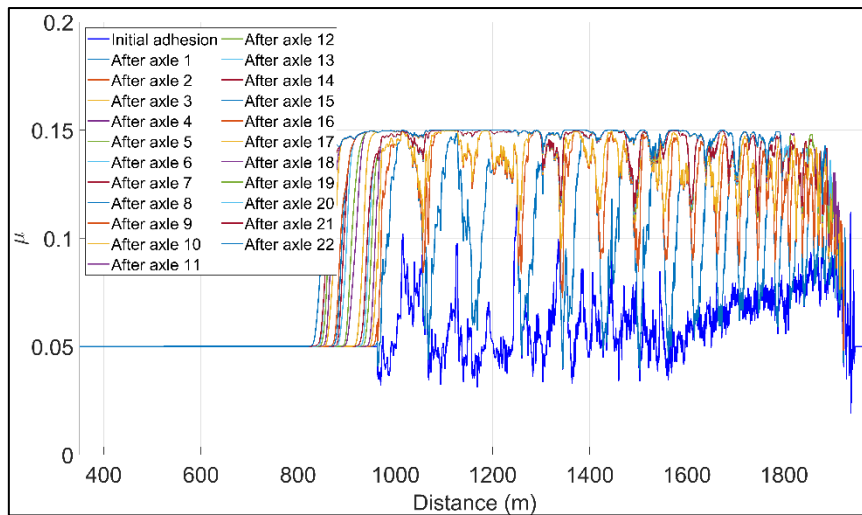
### 3. Numerical model and results

The developed model was validated by comparison with measurements provided by Bombardier Transportation from on-track braking tests carried out with the Regio 2N ONO train (10 cars and 11 bogies) in wet conditions (sprayed rail using 6% concentration soap). The main concern here is to study the effect of axles sliding on cleaning the rail and recovering adhesion. Thus, the EMB wasn't activated in the chosen reference test. The main initial settings of the simulation are summarized in Table 2.

**Table 2: Initial setting of braking simulation using VOCO**

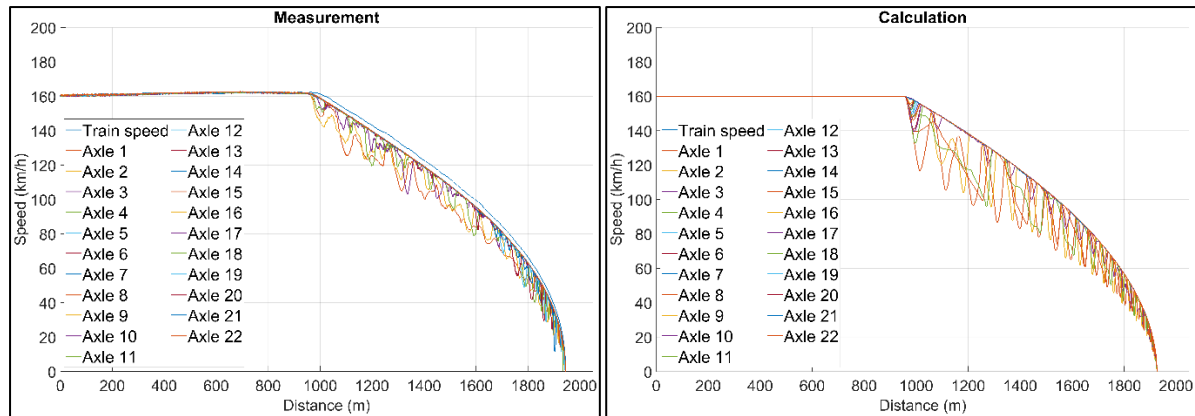
<i>Parameter</i>	<i>Unit</i>	<i>Value</i>
Initial speed	km/h	160
$\mu_0$	--	See Fig.3
$\mu_{max}$	--	0.15
$P_0$	Watt	20 kW
Time step $\Delta t$	s	3.e-4

The initial and the recovered simulated adhesion are shown in Figure 3. The variation of the initial adhesion  $\mu_0$  in distance is mainly due to the variation of the deceleration  $\dot{\omega}_a$  of the first sliding axle in expression (3). When axle  $i$  rolls over a position of the rail, adhesion left behind it increases due to sliding until reaching the maximum value  $\mu_{max}$ . Figure 3 shows that  $\mu_{max}$  is reached in this case after the passage of only 4 axles. The oscillation of adhesion left behind these 4 axles is due to how the WSP operates as the regenerated adhesion depends directly on the increase or the decrease of the sliding ratio according to the algorithm presented in Table 1.



**Fig. 3: Adhesion using the adhesion recovery model with VOCO.**

Figure 4 shows a comparison between measurement and calculation for axles and train speeds. The measured braking distance in this example is 985 m while the calculated one is 975 m which gives a relative difference less than 2%. This is a very good agreement between measurement and calculation for braking distance. The result shows also a good agreement for the train speed profile. However, the agreement is not well verified for speeds of the first 5 axles and especially when speed is less than 70 km/h. This discrepancy can be explained by the use of different WSP system between the measurement (real WSP device) and the calculation (simplified WSP algorithm). Thus, these promising results should be improved by replacing the current simulated WSP algorithm by the real one in a HIL procedure which will be done in the followings steps of the research. It is also possible to enhance the simplified WSP algorithm by adjusting the sliding limits  $s_1$ ,  $s_2$ ,  $s_3$  and  $s_4$  given in table 1.



**Fig. 4: Axles and train speed from Measurement (left) and calculation (right).**

#### 4. Conclusions

In this paper, a method that enables modeling of low adhesion recovery has been proposed and implemented in the MBS VOCO. The adhesion model is capable of reproducing the rail cleaning effect due to axles sliding during train braking. The model could be used to determine the restored adhesion along the track that can be considered as a new initial adhesion profile for further simulations.

The developed method is based on the calculation of the power dissipated by friction at the wheel-rail contact level. Adhesion recovery due to rail cleaning is considered by cumulating the dissipated powers due to all preceding axles sliding. To better simulate braking, a virtual WSP was introduced in VOCO. The calculations were compared with measurements provided from on-track braking tests. The result shows a very good agreement for braking distance and train speed. However, the agreement is less verified for the speed of the axles with a high sliding (so the first axles) due to the simplified WSP algorithm used in this work.

Future work will primarily focus first on improving the agreement between calculations and measurements by introducing a real WSP device inside the HIL environment and second on taking into account the adhesion recovery due to the wheel self-cleaning and due to the EMB.

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