SIMULATION OF THE CONTACT WIRE WEAR EVOLUTION IN HIGH SPEED OVERHEAD CONTACT LINES

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Key words: Wear, Contact wire, Pantograph, Railway catenary.

Abstract: *The overhead contact line or catenary is the structure composed of support elements and wires responsible for the power supply of the locomotive through sliding contact with the pantograph. This contact causes wear not only on the pantograph contact strips but also in the contact wire, which produces a reduction on its effective section and eventually its replacement, resulting in the stoppage of the rolling stock with its associate economical and operational drawbacks. For this reason, it is important for catenary designers to count with appropriate tools able to predict the contact wire wear behaviour for extending the service life of the system. This work proposes a strategy to simulate the long-term contact wire wear evolution considering the mutual influence between the dynamic behaviour and wear of the system. The method is based on two pillars: the efficient simulation of the catenary-pantograph dynamic interaction and a heuristic wear model which considers mechanical wear due to friction and electrical wear produced by Joule effect and electric arcs. With the proposed simulation tool, we analyse the effect on the long-term contact wire worn height of the train speed.*

1 INTRODUCTION

Power supply in electric trains is usually carried out by the sliding contact between the overhead contact line or catenary and the contact strips of the pantograph. As shown in Figure 1a, the catenary is composed of the contact wire, which is held by droppers from the messenger wire. All the cabling is regularly supported by brackets attached to posts. By means of steady arms, the catenary is arranged in a zig-zag shape. The pantograph mechanism (see Figure **??**) is mounted on the roof of the locomotive. Powered by a pneumatic system, the mechanism unfolds and the contact strips push against the contact wire.

This sliding contact produces wear in both the contact wire and contact strips. While the latter are relatively easy and cheap to replace, the substitution of a worn contact wire requires a higher investment and the stoppage of the rolling stock. For this reason, it is important to establish a correct maintenance strategy that predicts when you will need to replace the contact wire. To this end, numerical simulations can be an interesting tool not only to predict wear but also to help catenary designers to develop catenaries with longer service life.

Some authors have proposed different models to compute the normal wear rate (NWR) of the contact wire, which is defined as the volume of material removed in a kilometre of the wire. Specifically, heuristic wear models fitted by experimental measurements [1, 2] and models based on the Lim-Ashby wear maps [3, 4] are the most representative. Other research is focused on the experimental measurement of the contact wire thickness variation along successive years [5, 6] and the simulation of the pantograph-catenary dynamic interaction with the worn contact wire height profile. The main conclusions reveal that the greater the wear, the greater the oscillations in the contact force.

In this work, we propose a simulation strategy to predict the long-term contact wire wear

https://doi.org/10.4995/YIC2021.2021.12566

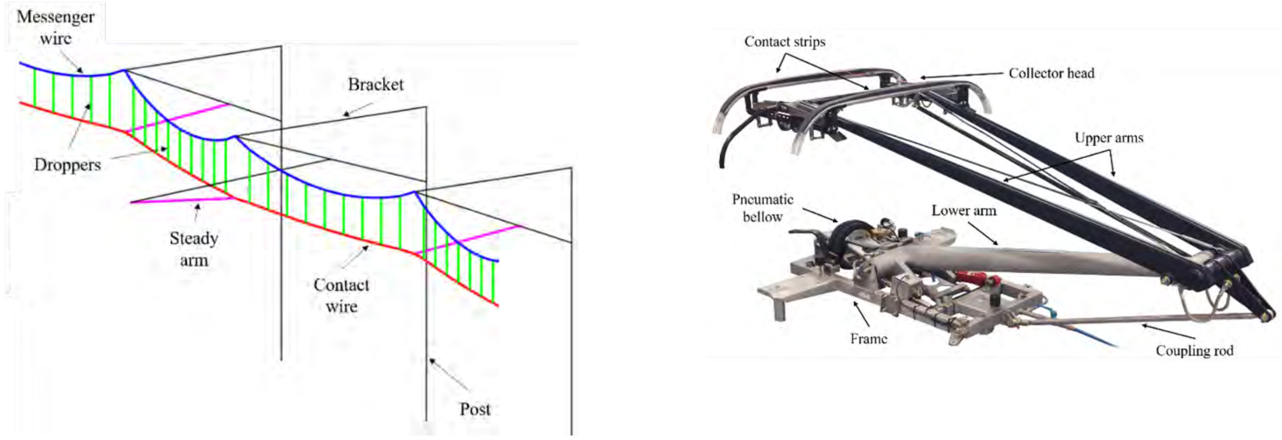

Figure 1: Main components a railway catenary (a) and pantograph (b)

evolvement considering the mutual influence between the dynamic behaviour of the system and the worn contact wire height profile. Starting from an unworn contact wire, this method allows to foresee when will be necessary to replace the contact wire and which are the most critical spots in which severe wear appears. The influence of the train velocity on the contact wire wear is also investigated.

2 LONG-TERM CONTACT WIRE WEAR SIMULATION

This section is devoted to give an overall view of the strategy proposed to compute the contact wire wear evolution which follows the flow diagram shown in Figure 2. Each of the steps involved in the procedure will be detailed in Section 3. The procedure starts by solving the initial configuration problem in which the nodal coordinates along with the element lengths are obtained for the Finite Element model of the nominal catenary with an unworn contact wire. From this point, a simulation loop is repeated until a given stopping criteria is reached, such as a certain percentage of the wire section is worn. The first step within this loop consists on solving the pantograph-catenary dynamic interaction. The main output obtained from this calculation is the contact force F_c between the pantograph and catenary contact wire. This force feeds the wear model to obtain the normal wear rate (NWR), which is the amount of area removed from each point of the contact wire due to wear. The removed section is then converted to an equivalent height following geometrical relations. At this step, as the contact wire section has changed, the total mass of the contact wire has decreased and therefore, it is needed to compute a static equilibrium problem to obtain the new position of the catenary and particularly the new contact wire height z_{cw}.

3 STAGES OF THE PROPOSED METHODOLOGY

This section is devoted to give a detailed insight of the models considered and the assumptions made in each of the stages that compose the proposed algorithm.

3.1 Initial configuration problem

In first place, the catenary model must be initialised. The Finite Element Method (FEM) with Absolute Nodal Coordinates Formulation (ANCF) elements is chosen to model the catenary cabling. The shape-finding problem consists of finding the nodal coordinates $\boldsymbol{q}$ and the undeformed element length $\boldsymbol{l_0}$ that fulfil both equilibrium equations and design constraints.

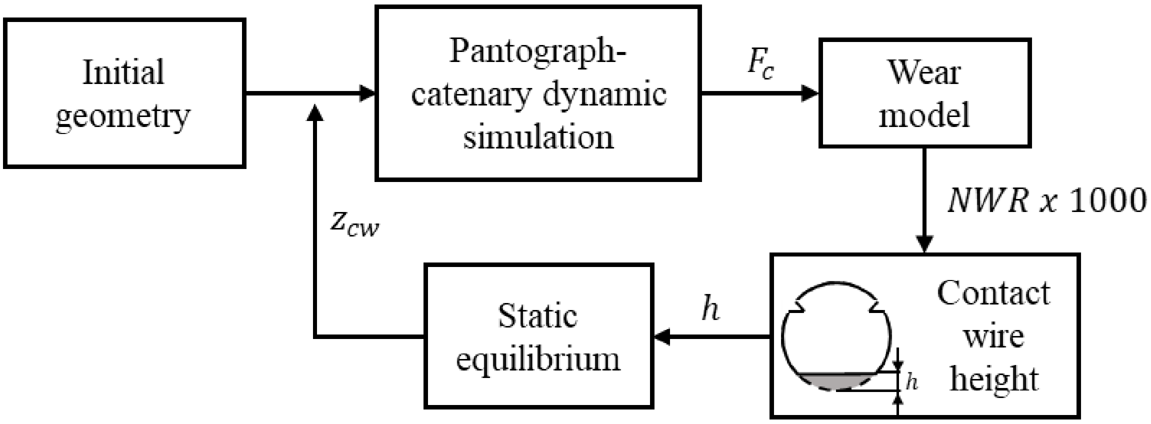

Figure 2: Flow diagram of the long-term contact wire wear simulation

The resultant non-linear problem is:

$$\begin{aligned} \boldsymbol{F_{int}}(\boldsymbol{q}, \boldsymbol{l_0}) + \boldsymbol{F_g}(\boldsymbol{l_0}) &= \boldsymbol{0} \\ \boldsymbol{C}(\boldsymbol{q}, \boldsymbol{l_0}) &= \boldsymbol{0} \end{aligned} \tag{1}$$

in which, $\boldsymbol{F_{int}}$ is the vector of internal forces, $\boldsymbol{F_g}$ is the vector of gravitational forces and $\boldsymbol{C}$ denotes for the design constraints such as tension of contact and messenger wires or position of dropper and stitch wire connection points. The interested reader is referred to [7] for a deeper explanation of the catenary initial configuration problem.

3.2 Pantograph-catenary dynamic interaction

The next step consists of solving the pantograph-catenary dynamic interaction problem. A lumped-mass model has been chosen to model the pantograph and the penalty method is used to consider the interaction between the pantograph and the contact wire.

This dynamic problem is governed by the following equation:

$$\boldsymbol{M}\ddot{\boldsymbol{u}} + \boldsymbol{C}\dot{\boldsymbol{u}} + \boldsymbol{K}\boldsymbol{u} = \boldsymbol{F} \tag{2}$$

in which, $\boldsymbol{M}$, $\boldsymbol{C}$ and $\boldsymbol{K}$ are the mass, Rayleigh damping and stiffness matrices respectively, $\boldsymbol{F}$ is the vector of external forces and $\boldsymbol{u}$, $\dot{\boldsymbol{u}}$ and $\ddot{\boldsymbol{u}}$ are the nodal displacement, velocity and acceleration vectors, respectively. This problem is also ruled by two nonlinearities, namely dropper slackening and pantograph contact losses.

For the simulation of the long-term evolvement of the contact wire wear, this dynamic problem must be solved hundreds of times. Thus, it is important to choose an efficient algorithm to perform the time integration of Eq. (2) with as low computation effort as possible. In this case, the fast algorithm proposed in [8] has been fully adopted.

3.3 Contact wire wear model

In this work we use the wear model of the copper contact wire proposed in [1]. This model differentiates three contributions on the total wear: (i) mechanical wear due to friction, (ii) electrical wear due to Joule effect of the current flow at the contact area and (iii) wear produced by electrical arcs when contact loss occurs. These three contributions to the contact wire wear are directly related to the three terms present in Eq. (3).

$$NWR = k_1 \left(\frac{1}{2}(1 + \frac{I_c}{I_0})\right)^{-\alpha} \left(\frac{F_c}{F_0}\right)^{\beta} \frac{F_c}{H} + k_2 \frac{R_c I_c^2}{Hv}(1-u) + k_3 \frac{V_a I_c}{v H_m \rho} u \tag{3}$$

The NWR represents the worn section and it is given in mm^2. The main factors that determine the wear rate are the electric current I_c, the sliding speed v and the contact force F_c. In this work we assume that F_c remains unaltered during a given number of pantograph passages in which it is not necessary to solve the dynamic interaction problem. Specifically, we have checked that 1000 passages gives a good balance between accuracy of the results and efficiency of the overall simulation.

A detailed description of all the parameters involved in the wear model is provided in [1] and unless otherwise indicated, we have kept the parameter values given in that reference. The only changes are the current intensity I_c = 300 A which is supposed constant, the contact force F_c and the appearance of contact loss u which come from the dynamic simulation and the electrical contact resistance R_c which, for a contact between a copper contact wire and a graphite contact strip, depends on the contact force as experimentally stablished in [9]:

$$R_c = 0.015 + 0.18e^{-(\frac{F_c-4}{7})} \tag{4}$$

3.4 Worn section height

The objective of this step of the proposed algorithm is to compute the total worn height h of the contact wire. For a contact wire section of radius R with an initial worn section A_0 (coloured region in Figure 3), the worn height due to the NWR produced by an additional thousand pantograph passages (grated area in Figure 2) is obtained from Eq. (5), in which the angle θ is first computed by solving the nonlinear Eq. (6), being $A = A_0 + 1000NWR$.

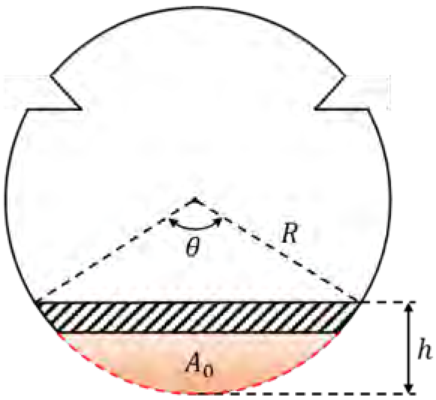

Figure 3: Worn section and worn height

$$h = R(1 - \cos\frac{\theta}{2}) \tag{5}$$

$$\frac{R^2}{2}(\theta - \sin\theta) - A = 0 \tag{6}$$

3.5 Static equilibrium

Once the contact wire height profile has been updated, it is important to note that the contact wire section has been reduced and therefore, the mass per unit length is modified. This weight loss modifies the force balance in the catenary model. That is why a static equilibrium problem is solved at this stage of the algorithm. This problem consists of solving Eq. (7) to obtain the new nodal coordinates that satisfy force equilibrium.

$$\boldsymbol{F_{int}}(\boldsymbol{q}) + \boldsymbol{F_g} = \boldsymbol{0} \tag{7}$$

Unless the initial configuration problem stated in Eq. (1), in this case, the element lengths are not set as unknowns.

4 NUMERICAL RESULTS

The numerical results presented in this work are obtained from the AC high speed contact line and the pantograph models provided in the standard EN-50318:2018 [10]. The initial contact wire section is 120 mm^2 and wear is only computed in a central region of the second catenary section, from kilometre point 400 to 800 m, to avoid boundary and transient effects. The stopping criteria for all the simulations performed is reaching a 20% of reduction on the contact wire section in a given kilometre point. This condition usually implies the replacement of the contact wire of the entire catenary section.

4.1 Nominal scenario

In this nominal case, the train speed is 300 km/h with an uplift force of 142.8 N acting on the pantograph mechanism. The main results obtained are shown in Figure 4.

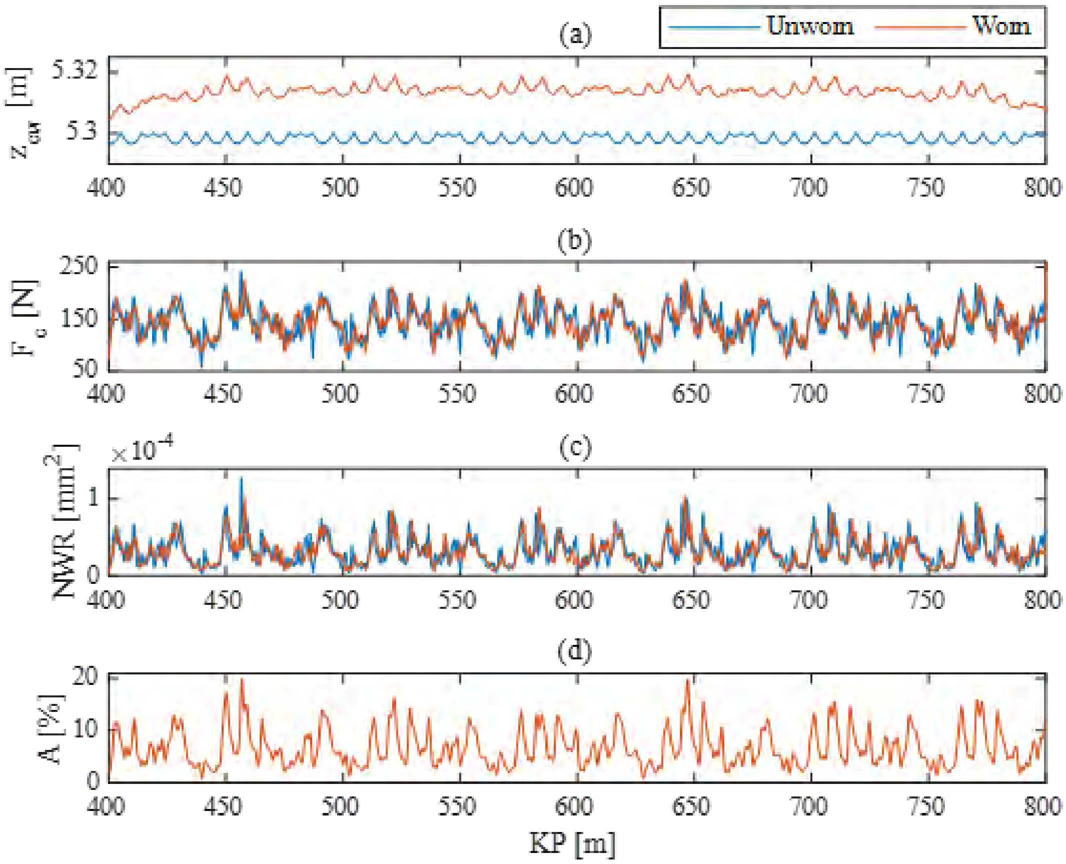

Figure 4: Comparison between the unworn and the worn catenaries in the nominal operating conditions: (a) contact wire height, (b) contact force, (c) normal wear ratio and (d) Percentage of worn area

The contact wire height is ploted in Figure 4a in which two effects can be distinguished. On the one hand, the main increase of the contact wire height (about 2 mm) is caused by the overall loss of weight. On the other hand, higher frequency irregularities are due to local wear effects. Figure 4b shows a comparison of contact force obtained from the unworn and the worn catenary. At first glance, a less oscilatory behaviour is observed in the contact force of the worn catenary, specially due to the disappearance of some local minima. The NWR obtained at the first and last pantograph passages is given in Figure 4c. An enlarged view of this plot is shown in Figure 5, in which a phase shift between the two wear rates is clearly observed.

This indicates that wear evolvement has a directional character which depends on the train travelling direction. This feature is also observed in the contact force. There is a clear direct relation between the contact force and the NWR since the main wear phenomena is mechanical friction in comparison to Joule wear.

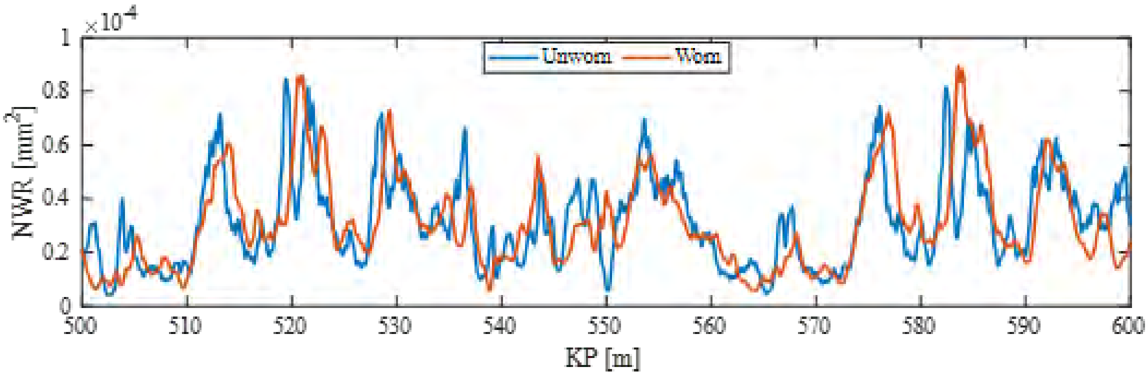

Figure 5: Enlarged view of the NWR obtained from the unworn and the worn catenary between kilometre points 500 and 600 m

Finally, in Figure 4d the percentage of worn section at the end of the simulation is shown. The 20% of worn area is reached at kilometre point 457 m after 250 dynamical simulations, which means 250.000 pantograph passages. Thus, this method provides a useful tool to foresee the life service period of a given catenary section.

4.2 Influence of train speed

It is well known that train speed has an important effect on the pantograph-catenary contact force and therefore, it is expected to also have it on the contact wire wear. In this section we compare the wear results obtained from simulations in which the pantograph travels at 200, 250, 300 and 350 km/h respectively. All the other parameters have been kept constant.

Figure 6 shows a comparison between the unworn and the worn catenary of the standard deviation σ, the maximum contact force F_c^{max} and the minimum contact force F_c^{min} for a different train speed. These results indicate that the worn catenary interacts with the pantograph producing a smother contact force than the unworn catenary as reflected by the lower value of $sigma$ for all the studied velocities. This trend is confirmed by the lower values of the maximum force and the higher values of the minimum force found in the worn catenary. The relative variation of any of these values is also indicated in Figure 6. In general, such variations become more significative with the increase of train speed. This means that the contact wire wear evolvement tends to form a contact wire height profile that smoothes the contact force so that wear decelerates and the chance of electric arcs due to contact loss decreases.

The percentage of contact wire worn section is shown in Figure 7 for the four studied velocities. The limit of 20% of section reduction is reached at different kilometer points in each case (circles in Figure 7). The number of pantograph passages necessary to reach this value and replace the contact wire is 367.000, 350.000, 250.000 and 173.000 for the wear simulation with 200, 250, 300 and 350 km/h respectively.

The position of steady arms is marked with vertical dashed lines in Figure 7. For this catenary, the points that suffer the highest wear are located at midspan because the contact force presents higher values at this region.

It is important to mention that at low velocities the mean wear is higher, and there are several points with a worn section close to the 20% of the initial contact wire section. However, at high velocities most of the contact wire length suffers low wear while only a few local points

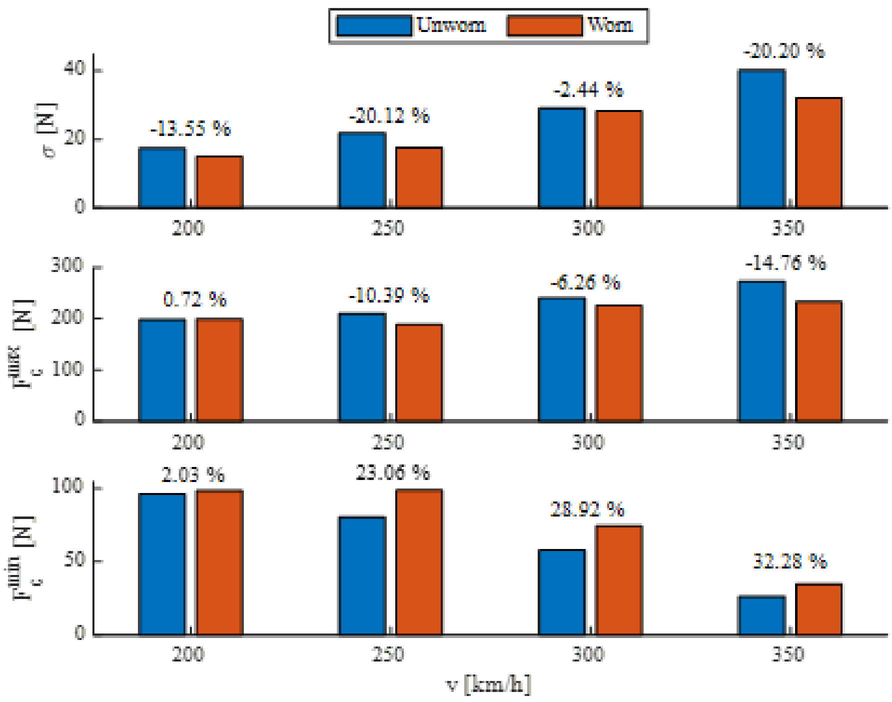

Figure 6: Statistics of the contact force under different train speeds for the unworn and the worn catenary

present severe wear. This implies to replace the whole contact wire of the catenary section because only in a few local spots the contact wire section has been reduced to its limit.

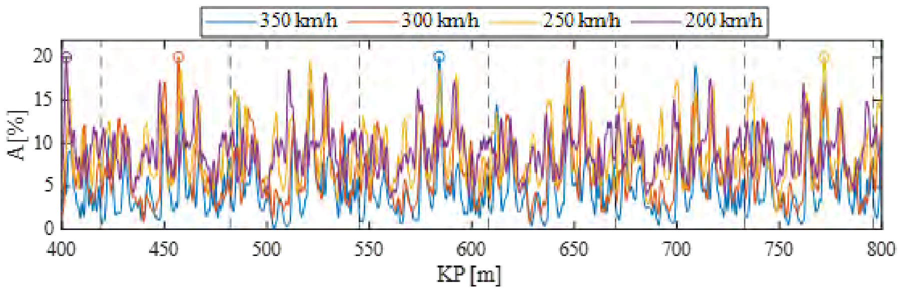

Figure 7: Percentage worn section along the contact wire for different train speeds

The higher overall amount of wear produced at low velocities is directly reflected in a higher contact wire height profile as shown in Figure 8. Specifically, the mean percentage of worn section is 9.11, 8.82, 6.76 and 4.85% for 200, 250, 300 and 350 km/h respectively.

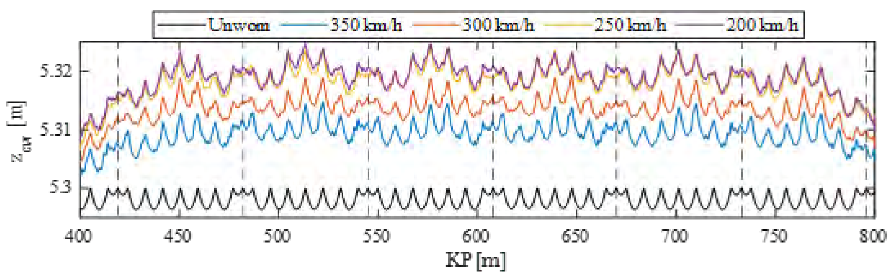

Figure 8: Contact wire height profile for the unworn catenary and the worn catenary when the pantograph travels at different velocities

5 CONCLUSIONS

This work proposes a simulation strategy to compute the long-term evolution of the contact wire wear for high-speed catenaries. The method uses an efficient dynamic solver of the pantograph-catenary interaction problem and a well-stablished contact wire wear model. As a novelty compared to other related works, the proposed algorithm considers the change in the catenary equilibrium position produced by the loss of material in the contact wire.

To exemplify the capabilities of the proposed method, it has been applied to a given catenary. Results such as the contact wire height profile, the contact force or the percentage of worn section were obtained for the nominal scenario concluding that wear evolution tends to provide a contact wire height that produces a smoother contact force so that, in a certain way, it seems to be beneficial for the current collection quality.

The effect of train speed on the contact wire wear has been also analysed. The main conclusion drawn from these simulations is that the increase of speed produces the localisation of wear on a few punctual regions of the contact wire, leading to its replacement even though on average it is little worn.

It is important to mention that this is an initial work on this field. Thus, the results and conclusions obtained cannot be extrapolated generally to other catenary-pantograph couples and they also need experimental measurements to be fully confirmed.

6 ACKNOWLEDGEMENTS

The authors would like to acknowledge the financial support received from the Spanish Ministry of Economy, Industry and Competitiveness (TRA2017-84736-R).

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