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# Optimization of a bogie primary suspension damping to reduce wear in railway operations

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## Abstract

An optimization problem is formulated to attain the vector of optimized primary suspension passive dampers of a bogie in order to minimize wear in railway applications. A mechanical system with five degrees of freedom (DOF) comprising a single rigid wheelset attached to a fixed bogie frame is chosen to explore the effects of primary suspension damping components on wear. Different operational scenarios including tangent and curved tracks together with different levels of track irregularities are introduced to be used as inputs to model. The equations of motion of the system are obtained and the FASTSIM algorithm is employed to relate the creepages and the corresponding creep forces in different directions. At vehicle maximum admissible speed and a given set of operational scenarios, the optimized values of the primary suspension passive dampers in longitudinal, lateral and vertical directions are found through a genetic algorithm optimization routine in MATLAB. The outcomes of current research can not only be used to minimize wear in railway operation as well as reduce track access charges and maintenance costs, but also give insight into designing adaptive bogies.

**Keywords:** *optimization, wear number, primary suspension damper, genetic algorithm, FASTSIM, passive control.*

## 1 Introduction

Railway technology provides one of the most important and efficient ways of transportation. In order to improve the cost efficiency of railway operation it is desirable to run the vehicle at maximum allowed speed to reduce track access charges while, having minimum wear. These two criteria are generally in conflict. Therefore, in order to increase the cost efficiency, it is required to find a trade-off between resulting wear in system and vehicle's speed. Track condition and wheel profile can affect bogie dynamics behaviour and wear. Well qualified tracks and optimized wheel profiles provide less wear and higher speeds on different operational scenarios. Dynamics behaviour of bogie on curves as well as effects of wear on operational performance, wheel and rail profiles also corrugation growth is explored in [1-6]. In this paper, it is assumed that track condition and wheel profiles are given and the focus is to achieve higher efficiency by changing bogie dynamics parameters.

Primary suspension system components, can affect bogie dynamics from different perspectives such as maximum admissible speed, wear, safety, ride comfort and so on. In this regard, several researches with focus on bogie primary suspension components are done during the last decades. Application of either semi-active or active vibration control strategies using Magneto-Rheological (MR) dampers as well as other types of active components on bogie dynamics behaviour is another interesting point of research (especially for bogie secondary suspension system and ride comfort criterion), see e.g. [7,8]. However, active components can amend bogie performance, there are some drawbacks associated with such systems. For example, design and maintenance cost are higher than the cost for similar passive solutions. Risk of sensor failure, demand for sufficient number of actuators and additional power supply are some other problems in this field.

Passive elements on the other hand, can affect bogie dynamics behaviour, significantly. Although, stiffness and damping values associated with such components are merely unique and constant values. As a result, such components cannot be adjusted with respect to different operational scenarios to improve the vehicle performance. Consequently, it is inevitable to formulate and solve several optimization problems to detect the optimized values of passive components that guarantee the best operational efficiency. In this regard, several researches on this particular field are done, see e.g. [9-12]. The genetic algorithm based multiobjective optimization of bogie suspension components with respect to safety and ride comfort issues is investigated in [13]. Results for a half car as well as a three car railway vehicle model in

GENSYS proved the efficiency and reliability of such optimization routines.

The ultimate goal of the current study is to improve the cost efficiency of railway operation (reducing wear and increasing speed, particularly) with focus on optimization of primary suspension dampers. In other words, for given sets of operational scenarios, effects of bogie primary suspension dampers on wear are investigated. In this regard, an optimization problem is defined to yield the optimized values of bogie primary dampers which will guarantee minimum wear at vehicle's maximum admissible speed on different operational scenarios. Here, a single wheelset with five DOF is chosen for the analysis. In order to have reliable system dynamics response as well as computational efficiency, a fast and reliable contact model is required. FASTSIM algorithm is able to predict the contact creep forces with a satisfactory level of accuracy and speed up the computation time, simultaneously [14]. Therefore, FASTSIM algorithm is chosen here for the analysis. Genetic algorithm optimization routine in MATLAB is employed to minimize wear objective function which is measured based on wear number. The outcomes of current study not only can improve the operational efficiency in passive case, but also provide useful insight into designing adaptive bogie using switching or other types of semi-active control techniques.

## 2 Modeling

A single wheelset with 5 degrees of freedom (DOFs) is considered. The wheelset is assumed to be rigid and is connected to the bogie frame by linear springs and dampers in longitudinal, lateral and vertical directions. Among all the possible motions of the wheelset only torsional angle along the wheelset axle is omitted. The primary suspension of the bogie system and corresponding degrees of freedom are shown in Figure 1.

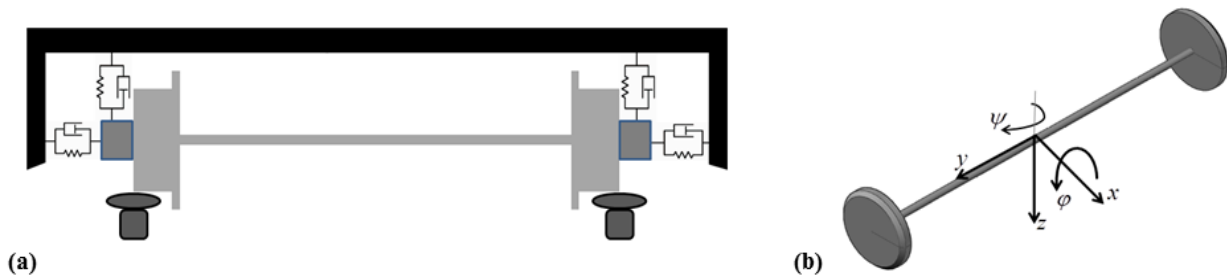


Figure 1. a) Primary suspension of the bogie; b) Corresponding DOFs

Using the trajectory coordinate described in [15], the equations of motion for the considered mechanical system are expressed as follows:

$$\begin{bmatrix} \mathbf{M} & \mathbf{\Phi}^T \\ \mathbf{\Phi} & \mathbf{0} \end{bmatrix} \begin{bmatrix} \ddot{\mathbf{p}} \\ \ddot{\boldsymbol{\lambda}} \end{bmatrix} = \begin{bmatrix} \mathbf{Q}_e + \mathbf{Q}_v \\ \mathbf{Q}_d \end{bmatrix} \quad (1)$$

$\mathbf{p} = [s, y, z, \psi, \varphi]$  is the vector of generalized coordinates of the wheelset.  $s$  is the track arc length travelled by the wheelset.  $\mathbf{M}$  is the system mass matrix corresponding to the trajectory coordinates,  $\mathbf{Q}_e$  is the vector of applied forces on system,  $\mathbf{Q}_v$  is the vector of coriolis and centrifugal forces,  $\mathbf{\Phi}$  is the kinematic constraint Jacobian matrix,  $\boldsymbol{\lambda}$  is vector of Lagrange multipliers, and  $\mathbf{Q}_d$  is the vector obtaining from differentiating constraint equation twice with respect to time. For further information regarding application of trajectory coordinates in railway analysis, see e.g. [15].

Towards obtaining the general forces acting on the wheelset, the track-wheel interaction should be addressed and the corresponding contact problem should be solved. There are several contact theories with different levels of accuracy such as Kalker's linear, Vermeulen-Johnson and others available in the literature to obtain the contact forces between wheel and rail [15,16]. Since, optimization is a time costly process it is required to have a relatively fast and reliable contact theory to increase the computational efficiency of optimization. FASTSIM algorithm works based on the simplified version of rolling contact theory and is able to estimate the longitudinal and lateral creep contact forces, as well as spin creepages with a satisfactory level of accuracy [14]. Using such algorithm can speed up the objective function evaluation in optimization routines, significantly. Therefore, FASTSIM algorithm is chosen here to find the relationship between creepages and the corresponding creep contact forces in different directions.

Ideal unworn *S1002* and *UIC60* profiles are chosen to approximate wheel and rail functions, respectively. In order to calculate general forces acting on the wheelset, it is necessary to calculate rolling radii and contact angles corresponding

to each wheel. There are several possibilities to find the contact point positions on wheel and rail. For example, look up tables coming from measurement data as well as some analytical methods which works based on the wheel and rail profile parameterization [17,18] could be useful in this field. However, computational burden of these methods is almost heavy. As described earlier, it is extremely important to employ computationally efficient routines and methods for optimization to speed up the process. On the other hand, it is not necessary to calculate the contact point positions with very high accuracy in most of the applications and a suitable estimation for that can represent the actual behaviour of the system with a satisfactory level of accuracy. Consequently, in order to improve the computational efficiency, it is assumed that the rolling radii and contact angles remain constant and equal to the corresponding nominal values during the analysis.

Although, wheels and track are considered as rigid bodies, it is assumed that elastic contact rules are governed at the contact area and two bodies are allowed to penetrate. The indentation value is then used in a nonlinear spring and damping based model to estimate the normal contact force between wheel and rail [17].

The longitudinal, lateral and spin creepages along with the normal contact force, contact area semi-axis and other parameters are applied as input variables to the FASTSIM algorithm in order to calculate longitudinal, lateral and spin creep forces acting on each wheel. Therefore, at each particular time of the analysis, one can fully describe the overall contact forces acting the wheelset.

## 2.1 Operational scenarios

Different types of operational scenarios including tangent and curved tracks with different radius of curvature and super elevation angels are examined and effects of primary suspension on each case are investigated. It is also assumed that two types of track irregularities exist: random track irregularities in the lateral direction and vertical track irregularities with harmonic nature.

Uniformly distributed random white noise generated by MATLAB `rand` function is applied as the track irregularity in the lateral direction. While, the vertical track irregularities are modeled using a stationary stochastic method and expressed as the following one-sided density function, see e.g. [19]:

$$\Theta(\Omega) = A \frac{\Omega_c^2}{(\Omega_r^2 + \Omega^2)(\Omega_c^2 + \Omega^2)}, \quad (2)$$

where,  $\Omega_c = 0.8246$  rad/m and  $\Omega_r = 0.0206$  rad/m.  $\Omega$  is the spatial angular velocity of the irregularities and coefficient  $A$  is the scaling factor used to define the amplitude of vertical track irregularities and should be chosen within the following range:  $A_{low} = 0.59233 \times 10^{-6}$  rad.m and  $A_{high} = 1.58610 \times 10^{-6}$  rad.m. It should be noted that  $A = 0.7930 \times 10^{-6}$  rad.m in this study.

Following the descriptions given in [13] the excitation profile can be expressed in terms of a harmonic series:

$$u(x) = \sqrt{2} \sum_{n=0}^{N-1} a_n \cos(\Omega_n x + \theta_n), \quad (3)$$

here,  $\theta_n$  are uniformly distributed phase angles in the range  $[0, 2\pi]$ ,  $\Omega_n = n\Omega_u / N$ ,  $\Omega_u$  is the highest frequency and coefficients  $a_n$  are as follows:

$$a_0 = 0, \quad a_1 = \sqrt{\left(\frac{\Theta(\Delta\Omega)}{2\pi} + \frac{\Theta(0)}{3\pi}\right)\Delta\Omega}, \quad a_2 = \sqrt{\left(\frac{\Theta(2\Delta\Omega)}{2\pi} + \frac{\Theta(0)}{12\pi}\right)\Delta\Omega} \quad \text{and} \quad a_n = \sqrt{\frac{\Theta(\Omega_n)}{2\pi}\Delta\Omega}, \quad \text{for } N=3, 4, \dots, N-1.$$

The harmonic functions generated by Eq. (3) are applied as the track irregularities in the vertical direction.

## 2.2 Objective functions

Any proposal for new designs and/or efficiency improvement in current systems requires meeting some threshold

constraints coming from various standards and manuals. In railway applications, ride comfort, safety and wear are some of the most prominent criteria. It is almost possible to measure these parameters in many different ways depending on the railway standards.

As aforementioned, the ultimate goal of the current research is to optimize the primary damping characteristics to minimize wear on a given operational scenario. Hence, wear is an objective function for optimization here. Furthermore, the proposed optimized values of design parameters should also satisfy ride comfort and safety issues.

It is often customary to span vehicle's accelerations on the floor of carbody as a measure of ride comfort. In order to make the measured accelerations a better representative of human body response to external excitations, different standards like Wertungszahl (Wz), ISO and EN introduce some filters to yield the frequency weighted accelerations for ride comfort analysis. Since, the dynamics behavior of a single wheelset is considered here and carbody motion is totally dismissed it is impossible to follow the described methods in ride comfort evaluation. However, in order to make a comparison between the optimization results obtained from different parts of this paper, the root mean square (RMS) of the wheelset accelerations in longitudinal, lateral and vertical directions is introduced as follows:

$$\Gamma_c = \sqrt{\frac{1}{t_f - t_0} \int_{t_0}^{t_f} (\mathbf{a}^w(t))^2 dt}, \quad (4)$$

where,  $\Gamma_c$  denotes comfort objective function,  $\mathbf{a}^w(t)$  is the vector of wheelset acceleration.  $t_0$  and  $t_f$  are the initial and final instants of time, respectively.

It is possible to investigate a high speed train (HST) safety from different points of view such as: risk of derailment, critical hunting speed, wear between rail and wheel which may causes some failure and cracks in the vehicle, fault in a track switching system or brakes and so on. It should be noted that the focus on vehicle safety issue here is based on the dynamics and vibration design parameters. Shift force which is one of the most widely-used and well-known parameters in railway vehicles safety analysis is applied here and expressed as [13]:

$$\mathbf{S}(t) = \mathbf{F}_y^{\text{Left}} - \mathbf{F}_y^{\text{Right}}, \quad (5)$$

where,  $\mathbf{F}_y$  denotes the lateral force acting on each wheel. The shift force given in Eq. (5) usually should be filtered with a 20 Hz low-pass filter and the values around 2 m of the peak in shift force curve have to be used in safety analysis, see e.g. [13]. A limit of 99.85% percentile of the shift force calculated based on the prescribed method is considered as the safety objective function  $\Gamma_s$  here, i.e.  $\Gamma_s = \max \{S_{20\text{Hz}, 2\text{m}, 99.85\%}\}$ .

In the present study, the wear objective function  $\Gamma_w$  used to estimate the rate of wear in rail and wheels is defined as follows:

$$\Gamma_w = \sqrt{\frac{1}{t_f - t_0} \int_{t_0}^{t_f} \frac{1}{2} \sum_{i=1}^2 (T_\gamma^i)^2 dt}, \quad (6)$$

where,  $T_\gamma^i$  is the energy dissipation in the contact patch called wear number [13,20].

$$T_\gamma^i = R_x^i \xi_x^i + R_y^i \xi_y^i + M_{xy}^i \xi_{xy}^i, \quad (7)$$

here,  $R_x^i, R_y^i, M_{xy}^i$  are longitudinal, lateral and spin creep contact forces and  $\xi_x^i, \xi_y^i, \xi_{xy}^i$  are the corresponding creepages. The subscript  $i$  denotes right and left wheels (*i.e.*  $i$ =left wheel, right wheel).

From Eqs. (4-7) it is obvious that in order to evaluate all the prescribed objective functions, system dynamics response should be determined first. Therefore, Eq. (1) should be solved in each optimization loop to yield the system dynamics response and the corresponding objective functions.

### 2.3 Optimization

As aforementioned, vehicle's speed, ride comfort, safety and wear are the most interesting factors in evaluating the cost efficiency of railway operations. The abovementioned objective functions are highly interconnected and an improvement in each can deteriorate the rest. For example, increasing the vehicle's speed can reduce the track access charges. However, that aggravates the ride comfort, safety and wear levels. Therefore, in order to attain the best

operational efficiency, an optimization problem should be defined and solved. In the case of current study, the ultimate aim is to optimize primary suspension damping components to have the possibility to run the vehicle at maximum admissible speed and minimize wear on different operational scenarios. Therefore, the following optimization problem is formulated.

For the system described by Eq. (1) subject to given initial state, prescribed structural system parameters and given operational scenarios, it is required to determine the vector of design parameters  $\mathbf{d}^* = [c_x^*, c_y^*, c_z^*]^T$  (optimized primary suspension dampers in longitudinal, lateral and vertical directions) and the vehicle's maximum admissible speed  $V_{\max}^*$  such that the following conditions are guaranteed:

$$\min_{\mathbf{d}, V} \Gamma_W(\mathbf{d}, V) = \Gamma_W(\mathbf{d}^*, V_{\max}^*) = \Gamma_W^{\min} \leq \Gamma_W^{\max} \quad (8a)$$

$$\Gamma_C(\mathbf{d}^*, V_{\max}^*) \leq \Gamma_C^{\max} \quad (8b)$$

$$\Gamma_S(\mathbf{d}^*, V_{\max}^*) \leq \Gamma_S^{\max} \quad (8c)$$

Here,  $\Gamma_W^{\max}$ ,  $\Gamma_C^{\max}$  and  $\Gamma_S^{\max}$  are the maximum admissible values of wear, comfort and safety objective functions, respectively. Indeed, Eqs. (8) express the mathematical form of optimization problem with respect to speed and wear, while the ride comfort and safety objective functions are taken as a threshold.

For the formulated problem, it is possible to take an evolutionary multiobjective optimization algorithm (EMOA) into consideration to perform the optimization process. The methodology works based on the genetic algorithm concept implemented in MATLAB `gamultiobj` routine. The general overview of the implemented optimization routine is portrayed in Figure 2.

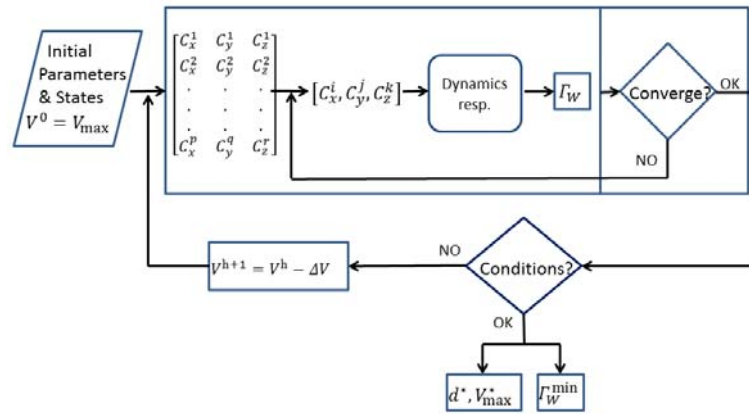


Figure 2. Overview of the implemented optimization routine.

For a given set of operational scenarios, structural parameters and initial states, the simulation starts at vehicle's maximum admissible speed ( $V_{\max}$ ). In each iteration, based on the predefined lower and upper bounds for the design parameters (*i.e.*  $C_x \in [C_x^l \ C_x^p]$ ,  $C_y \in [C_y^l \ C_y^q]$  and  $C_z \in [C_z^l \ C_z^r]$ ), the `gamultiobj` routine picks three values for the longitudinal, lateral and vertical primary dampers (*i.e.*  $C_x^i$ ,  $C_y^j$  and  $C_z^k$ ) and evaluates the wear objective function. The optimization routine ceases, once the convergence achieved. At this stage, the ride comfort, safety and wear objective functions associated with the achieved optimized values of design parameters must be compared with the corresponding maximum admissible values of the ride comfort  $\Gamma_C^{\max}$ , safety  $\Gamma_S^{\max}$  and wear  $\Gamma_W^{\max}$  to make sure if the



design requirements are satisfied.

For a specific vehicle's speed, if at least one point assures all the necessary conditions, the procedure will be terminated. As a result, the current vehicle's speed denotes the maximum admissible velocity  $V_{\max}^*$  and the optimization results provide information regarding the optimized design parameters and minimum value of the objective function. In contrast, if the optimization fails to satisfy the design conditions, the input vehicle's speed should be decreased by  $\Delta V$  and the procedure must be repeated.

The results obtained from such analysis not only provide useful information to improve the passive bogies, but also give insight into design adaptive vehicles. In the subsequent section the application of this method is shown through an example.

### 3 Results

Structural parameter data used for the single wheelset model shown in Figure 1 are given in Table 1 and chosen as close as possible to [17]. Before starting the optimization, it is good to check the sensitivity of the dynamics response and wear objective function with respect to some of the input data such as forward speed, operational scenario, design variables and so on. That could help to detect those parameters that can affect the dynamics response and wear, significantly. Using such sensitivity analysis, one can narrow down the input parameters for the optimization and speed up the process.

After the simplifications discussed in the previous sections, a satisfactory level of computation time for the system dynamics response analysis was achieved. Therefore, it is not necessary to perform deep sensitivity analysis here and reduce the number of varying parameters in optimization. However, as an example, variations of wear objective function with respect to different lateral damping coefficients, vehicle speeds and vertical track irregularities are demonstrated in Figure 2.

**Table 1.** Structural parameters data

Variable	Description	Value
$m_w$	Wheelset mass	1568 kg
$I_{xx}$	Moment of inertia along x axis	656 kg.m <sup>2</sup>
$I_{yy}$	Moment of inertia along y axis	168 kg.m <sup>2</sup>
$I_{zz}$	Moment of inertia along z axis	656 kg.m <sup>2</sup>
$W$	External vertical load	98 kN
$K_x$	Longitudinal spring stiffness	$1.35 \times 10^5$ N/m
$K_y$	Lateral spring stiffness	$2.5 \times 10^5$ N/m
$K_z$	Vertical spring stiffness	$2.5 \times 10^5$ N/m
$\mu$	Coefficient of friction	0.15
$E$	Elasticity module	210 GPa
$b$	Distance between longitudinal springs	0.9 m
$2s$	Gage value	1432 mm

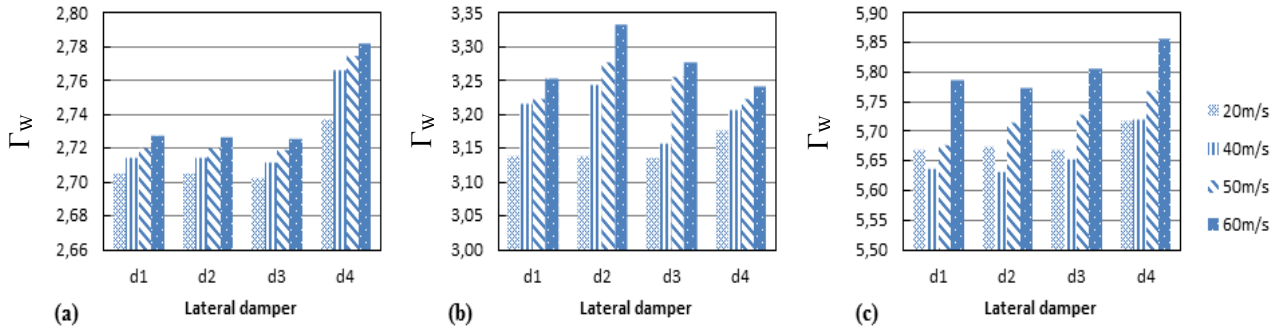
It should be noted that no lateral track irregularities are considered for this case. Furthermore, the damping values in longitudinal and vertical ( $C_x$  and  $C_z$ ) as well as lateral direction ( $C_y=d1, d2, d3, d4$ ) are given in Table 2.

**Table 2.** Damping values in different directions (N/m.s)

Longitudinal	Vertical	Lateral ( $C_y$ )			
$C_x$	$C_z$	d1	d2	d3	d4
$1.0 \times 10^5$	$1.0 \times 10^5$	0.0	$1.0 \times 10^3$	$1.0 \times 10^4$	$1.0 \times 10^5$

As expected, increasing speed and/or track irregularity amplitudes leads to higher values of  $\Gamma_w$  (see Figure

2). That means higher wear and maintenance cost. It is also shown that the vehicle performance is a function of damping parameters. For instance, as follows from analysis of Figure 2 to minimize wear while running the vehicle with maximum speed of 60 m/s on ideal, track with low and high amplitude irregularities, d3, d4 and d2 lateral damping coefficients should be chosen, respectively. Therefore, one can achieve better performance by designing adaptive components and control strategies like the possibility to switch between optimized damping coefficients on each operational scenario and minimize the  $\Gamma_w$ .



**Figure 2.**  $\Gamma_w$  vs. lateral damper coefficient  $d_i$  for different railway vehicle speeds and track irregularities, a) ideal track; b) low amplitude irregularities; c) high amplitude irregularities

In order to start the optimization, it is necessary to define some of the input parameters to the optimization routine. The following initial guess for the damping parameters  $C_x^0 = 1 \times 10^5$  N/m.s,  $C_y^0 = 1 \times 10^3$  N/m.s and  $C_z^0 = 1 \times 10^5$  N/m.s are considered in the longitudinal, lateral and vertical directions, respectively. In addition, lower and upper bounds for the damping coefficients in all directions are  $B_l=0$  and  $B_u=5 \times 10^5$  N/m.s, respectively. Population size for the optimization is equal to 20.

The primary suspension damping optimization of bogie with respect to wear is formulated and solved for different wheelset speeds and various operational scenarios given in Table 3. It should be noted that in all these simulation cases, the wheelset is subject to similar random lateral and harmonic vertical track irregularities as described in previous section. In addition, the wear objective function is evaluated on  $L_s=500$  m length of the track travelled by the wheelset. It should be noted that the speed values for each simulation case are the maximum admissible values obtained from safety issue  $\Gamma_s$  as well as optimization.

**Table 3.** Different operational scenarios

Simulation case	Radius of curvature R (m)	Track Type	Super elevation angle $\phi_{se}$ (deg)	Velocity (m/s)
P <sub>1</sub>	$\infty$	Tangent	0	60
P <sub>2</sub>	2000	Large radius	8	50
P <sub>3</sub>	1000	Large radius	10	40
P <sub>4</sub>	500	Medium radius	12	30
P <sub>5</sub>	350	Small radius	14	25

The optimized values of the primary suspension damping components and relative improvements in the objective functions for different operational scenarios are presented in Figure 3 and Table 4, respectively. Therefore, the optimization problem defined by Eqs (8) has a solution. From the Table 4, it is clear that wear objective functions sensitive with respect to primary suspension damping components for different operational scenarios. Wear can be reduced on a small radius curve (P5) up to 11% for the vehicle running with highest admissible speed (25m/s) by choosing suitable values for damping coefficients.

In the case of longitudinal damper, the simulations have shown that relatively large values for  $C_x$  can reduce wear for tangent and large radius curve tracks (Figure 3). While, in order to reduce wear on medium or small radius curves, the longitudinal damper values should be decreased. Since longitudinal primary damper can suppress the yaw motion of wheelset as well as reduce wear on large radius curves, higher values for that parameter can be an advantageous on such operational scenarios. However, that could increase wear for smaller radius of curves. Semi-active control strategies (on-off or switching) could be a smart solution for that problem. Therefore, in order to have minimum wear during the

operational, such control techniques could activate higher and lower longitudinal damping values on large and small radius curves, respectively.

The optimization results have also shown that in order to have minimum wear for a single wheelset running on the prescribed operational scenarios while the radius of curvature ( $R$ ) decreases; the lateral damping value ( $C_y$ ) should be magnified, while the vertical damping ( $C_z$ ) has to be reduced (Figure 3). An exception for this conclusion is the case  $P_2$ - $P_3$  where the radius of curvature reduces, while the lateral and vertical damping coefficients should be decreased and increased, respectively. Case  $P_2$  needs large lateral and relatively small vertical dampers to provide minimum wear. It should be noted that the vehicle speed for simulations on each operational scenario is different and as discussed previously vehicle speed affects wear and optimization results drastically. Therefore, the optimized damping values obtained here not only depend on the operational scenario ( $R$  and  $\varphi_{se}$ ) but also on forward speed. In addition, success of any genetic algorithm based optimization routine depends on the defined population size, tolerances and initial guess for the design parameters. Inappropriate initial guess in such optimization routines can lead to a local minimum instead of the global optimum and that could be an important issue.

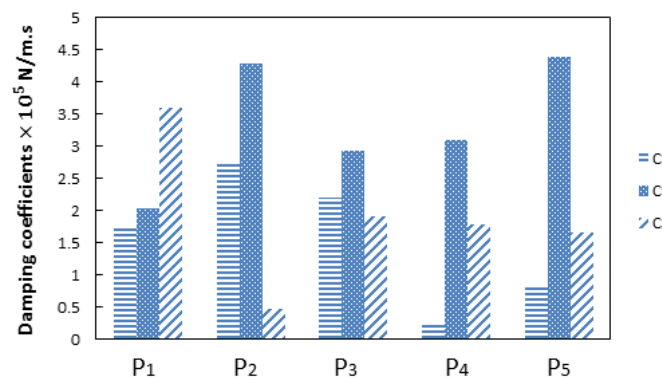


Figure 3. Optimized primary suspension damping

Table 4 shows how the obtained optimization results affect  $\Gamma_w$ ,  $\Gamma_s$  and  $\Gamma_c$  (in terms of relative percentile %) for different operational scenarios in comparison with the respective values of these objective functions obtained using initial guess for the primary suspension damping.

Table 4. Relative improvement in objective functions (%)

Case	$\Gamma_{rel}^w$ %	$\Gamma_{rel}^s$ %	$\Gamma_{rel}^c$ %
P <sub>1</sub>	0.72	-0.27	-0.82
P <sub>2</sub>	1.04	-1.41	-1.06
P <sub>3</sub>	1.50	32.09	47.12
P <sub>4</sub>	5.76	-30.78	-15.91
P <sub>5</sub>	11.23	-39.71	-33.74

It can be deduced that optimized values of design parameters (primary suspension dampers) can reduce wear and increase the cost efficiency of railway operation, significantly. In the case of tangent or large radius curve operational scenarios, this improvement is small while for medium and/or small radius curves the wear reductions are more noticeable (in considered numerical example - up to 11%). That is understandable inasmuch as wear generation on curves is much higher than the corresponding tangent or large radius curve operational scenarios.

It should be also noted that in the case of using optimized values of primary suspension dampers, ride comfort and safety status of the wheelset can be affected negatively in comparison with the values corresponding to initial guess as shown in Table 4. Since, the optimization is applied with respect to wear, ride comfort and safety objective functions could be either improve or deteriorate. However, as the numerical simulation for the considered system has shown ride comfort and safety status for optimized primary suspension damping are still within the admissible range.

The simulation results for the passive case can give insight into designing adaptive bogies. Semi-active vibration control

strategies using on-off switching and MR dampers could be one of the possible approaches here. For instance, in order to run the vehicle as fast as possible while giving minimum wear on a tangent track, then on large and medium radius curves described in Table 3, based on the current operational scenario switching between the optimized primary damper values given in Figure 3 could be useful. That could be considered as the future steps of this study.

## 4 Conclusion

The optimization of primary suspension dampers of a single rigid wheelset with respect to wear has been explored. Simulations have been performed on several operational scenarios including tangent and curved tracks with lateral and vertical track irregularities. The RMS value of wear number has been considered as the objective function for the optimization, while ride comfort and safety have been taken as thresholds. Genetic algorithm based multiobjective optimization routine is chosen for the analysis.

Dynamics response of the system on different operational scenarios has shown the sensitivity of objective functions in question with respect to primary suspension damping components and forward speed. The obtained optimized values of primary suspension dampers provided appropriate improvement in wear status as well as satisfactory results for the ride comfort and safety.

The results of this investigation could help to identify the optimized characteristics of primary suspension passive dampers on different scenarios and give some hints of designing of bogie with adaptive components (e.g. by using semi-active and/or active vibration control techniques for bogie primary suspension).

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## References

- [1] J. Brouzoulis, P. T. Torstensson, R. Stock and M. Ekh. Prediction of wear and plastic flow in rails—Test rig results, model calibration and numerical prediction. *Wear*, 271:92–99, 2011.
- [2] P. T. Torstensson and M. Schilke. Rail corrugation growth on small radius curves—Measurements and validation of a numerical prediction model. *Wear*, 303:381–396, 2013.
- [3] P. T. Torstensson and J. C. O. Nielsen. Simulation of dynamic vehicle–track interaction on small radius curves. *Vehicle System Dynamics*, Vol. 49, No. 11, 1711–1732, 2011.
- [4] J. Pombo, J. Ambrósio, M. Pereira, R. Lewis, R. Dwyer-Joyce, C. Ariaudo and N. Kuka. A study on wear evaluation of railway wheels based on multibody dynamics and wear computation. *Multibody System Dynamics*, 24:347–366, 2010.
- [5] J. Pombo, J. Ambrósio, M. Pereira, R. Lewis, R. Dwyer-Joyce, C. Ariaudo and N. Kuka. A railway wheel wear prediction tool based on a multibody software. *Journal of Theoretical and Applied Mechanics*, 48:751–770, 2010.
- [6] J. Pombo, J. Ambrósio, M. Pereira, R. Lewis, R. Verardi, C. Ariaudo and N. Kuka. Influence of track conditions and wheel wear state on the loads imposed on the infrastructure by railway vehicles. *Computers and Structures*, 89:1882–1894, 2011.
- [7] D. H. Wang and W. H. Liao. Semi-active suspension systems for railway vehicles using magnetorheological dampers. Part I: system integration and modelling. *Veh. Syst. Dyn.*, 47:1305–1325, 2009.
- [8] D. H. Wang and W. H. Liao. Semi-active suspension systems for railway vehicles using magnetorheological dampers. Part II: simulation and analysis. *Veh. Syst. Dyn.*, 47:1439–1471, 2009.
- [9] P. Eberhard, W. Schiehlen and D. Bestle. Some advantages of stochastic methods in multicriteria optimization of multibody systems, *Archive of Applied Mechanics*, 69: 543–554, 1999.
- [10] Y. He and J. J. McPhee. Design optimization of rail vehicles with passive and active suspensions: A combined approach using genetic algorithms and multibody dynamics. *Vehicle System Dynamics*, 37:397–408, 2002.
- [11] T. X. Mei and R. M. Goodall. Use of multiobjective genetic algorithms to optimize inter-vehicle active suspensions. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, 216: 53–63, 2002.
- [12] Y. He and J. McPhee. Multidisciplinary Optimization of Multibody Systems with Application to the Design of Rail Vehicles, *Multibody System Dynamics* 14: 111–135, 2005.

- [13] A. Johnsson, V. Berbyuk and M. Enelund. Pareto optimisation of railway bogie suspension damping to enhance safety and comfort, *Veh. Syst. Dyn.*, 50:9, 1379—1407, 2012.
- [14] J. J. Kalker. *Three-dimensional elastic bodies in rolling contact*. Springer, Dordrecht, 1990.
- [15] A. A. Shabana, K. E. Zaazaa and H. Sugiyama. *Railroad vehicle dynamics a computational approach*, Taylor & Francis Group, LLC, 2008.
- [16] V. K. Garg and R. V. Dukkipati. *Dynamics of Railway Vehicle Systems*. Academic Press, Canada, 1984.
- [17] A. A. Shabana, M. Tobaa, H. Sugiyama and K. E. Zaazaa. On the computer formulations of the wheel/rail contact problem. *Nonlinear Dynamics*, 40:169-193, 2005.
- [18] A. A. Shabana, K. E. Zaazaa, J. L. Escalona and J. R. Sany. Development of elastic force model for wheel/rail contact problems. *Journal of Sound and Vibration*, 269: 295-325, 2004.
- [19] H. Claus and W. Schiehlen. Modeling and simulation of railway bogie structural vibrations. *Veh. Syst. Dyn.*, 28: 538-552, 1998.
- [20] M. C. Burstow. Whole Life Rail Model Application and Development for RSSB – Continued Development of an RCF Damage Parameter, *AEATR-ES-2004-880* Issue 2, AEA, Derby, 2004.