Influence of Railway Wheel Profiles on Operational Vehicle Safety: Design and Analysis of Computer Experiments

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EXTENDED ABSTRACT

1 Introduction

Railway vehicles can transport a high number of people and commodities at the same time in a fast and energetically efficient way. As a result, railway transportation plays a fundamental role in modern transportation for a sustainable future. The interaction of forces between the wheels of the vehicle with the rail track in operation is vital for the proper functioning of the transport mode and safety. Wheels have a specific profile shape, whose characteristics are necessary for the curve negotiation and to avoid derailment. Some of the most important ones are a conic rolling tread and a flanged surface [1].

The shape of the wheel profiles is always changing in operation mainly due to the contact with the rails and maintenance standards establish operation windows for wheel profile geometric parameters. These windows aim to guarantee that the vehicle does not derail in operation conditions due to dynamic forces between the wheels and the rails, as well as to ensure the dimensional interoperability of the wheel with other systems. Additionally, train operating companies may also define their own stricter windows of operation inside the windows defined by the standards. These new windows may be redefined based on specific dimensional constraints of the train operating company or based on maintenance costs related to the degradation process of the wheels.

Regarding derailment due to dynamic forces between the wheels and the rails, limit values for wheel parameters related to the structural safety of the materials can be effectively defined. However, for other situations of derailment, such as flange climb or wheel unloading, the limits for wheel parameters are less straightforward to be defined. Railway dynamics is a complex system, having plenty of interactions between bodies and several specific combinations of running conditions may lead to these latter situations of derailment. Consequently, the simulation of all test scenarios to define limit values becomes very costly and time expensive in terms of field, laboratory and even computer experiments.

Having said this, the following research question may be formulated: are railway wheel profiles impacting vehicle safety during operation? Design and analysis of computer experiments (DACE) [2] can provide strategies to address this question in an efficient and robust way and help understand to what extent wheel parameter limits are defined based on the safety of vehicle dynamics rather than other considerations. As a result, objectives are set to: (i) select design variables; (ii) define experiments; (iii) evaluate vehicle responses; (iv) estimate surrogate models and perform a sensitivity analysis; (v) assess the impact of wheel parameters in vehicle safety during operation conditions.

Therefore, this work contributes to providing a robust assessment of the impact of railway wheel profiles on vehicle safety during operation that, to the best of the knowledge of the authors, has not been present in the literature so far. A proposed purely data-driven wheel profile generation approach of geometric modelling enables evaluating such a variety of test scenarios in the DACE. Moreover, this work goes through a real-world case study to illustrate its contributions, where condition monitoring data from railway companies are used, thus, being well-aligned with the current industry trends.

2 Problem description

This work explores the case study of a Portuguese passenger railway company, Fertagus, which operates on a single line from the Portuguese infrastructure manager, Infraestruturas de Portugal. Fertagus has a fleet of 18 trains of the same type and the line where they operate has an extension of approximately 54 km, linking 14 stations between Roma-Areeiro and Setúbal. As in Europe train operating companies manage their rolling stock not sharing information with infrastructure managers and vice versa, in what is called a policy of vertical separation, this work is developed ultimately with the perspective of train operators controlling their assets. EN 15313 establishes in-service wheel parameter windows. On top of this standard, Fertagus shrinks the operating windows. In turn, EN 13848 defines operation windows for track irregularities, in particular, it uses standard deviations (SDs) of the alignment and the longitudinal level as a function of the maximum velocities allowed on the rail tracks. Finally, EN 14363 defines tests, measurements, post-processing, and limit values for the acceptance of railway vehicles. In particular, this standard defines the limit value for potential flange climb derailment as 0.8, being this value the ratio of the dynamic lateral contact force Y over the dynamic vertical contact force Q on a wheel, Y/Q. In addition to this safety quantity, a wheel unloading criterion, $\Delta Q/Q_0$, is commonly specified and a typical limit value adopted in Europe is 0.6, being Q_0 the static wheel load and $\Delta Q = Q_0 - Q$.

3 Applied methods

Operation data is used to support this work, namely wheel profile data from inspection activities using laser equipment, vehicle instant speeds from a global positioning system and rail track data from inspection activities using an inspection vehicle. The design variables are chosen and pre-processed based on previous literature, standards and a proposed data-driven wheel profile generation approach of geometric modelling that uses real worn profiles and optimization to create realistic wheel profiles with the desired wheel parameters. Then, the experiments are defined using a Latin hypercube sampling approach that reduces spurious correlations between the experiments. Next, the vehicle responses are evaluated using the multibody dynamics commercial software VAMPIRE® Pro and are post-processed based on EN 14363. Subsequently, surrogate models are fit to the experiment data. Firstly, Gaussian processes (GPs) are applied, as they are linear predictors capable of representing highly non-linear functions. Consequently, they are well-suited to performing sensitivity analysis, as they are able to capture high-order effects of predictors. However, one of their limitations are parameter-based interpretations, which are important for decision-makers. Therefore, linear regression models are also performed. The parameters of GPs are obtained through maximum likelihood estimates using genetic algorithms, while the ones of linear models are estimated using ordinary least squares through stepwise regression. The sensitivity analysis is performed using Sobol indices. Afterwards, both surrogates are compared through cross-validated metrics and the response surface of the best surrogate is used for the safety assessment.

4 Results

Seven not correlated variables that have influence on the vehicle safety quantities are chosen to be varied in the DACE: load, speed, SDs of the alignment, SDs of the longitudinal level, tread diameter, flange height and flange thickness. The experiments consist of a round-trip of one vehicle between Roma-Areeiro and Setúbal run in VAMPIRE® Pro. Results of the vehicle responses and subsequent surrogates do not present values indicating the risk of flange climb. The same does not happen with the risk of wheel unloading. Sensitivity analyses performed to the GP models show that most of the variance is well explained by second-order sensitivities. Consequently, second-order linear models are also performed, which present better prediction metrics. As depicted in Figure 1, the response surface of the linear model indicate that there are operation zones with wheel unloading values over 0.6.

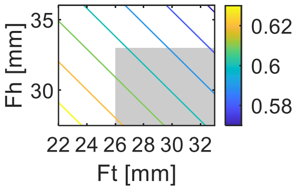

Figure1: Wheel unloading maximum predictions varying the flange height, *Fh*, and flange thickness, *Ft*, with average load, a real speeds profile, maximum allowed track irregularities and a tread diameter of 910 mm (shade: Fertagus operation envelope).

5 Conclusion

Evaluating the dynamic safety of a vehicle is not a straightforward task. A combination of several factors can indicate risk of derailment and be very case specific. As a result, establishing general use standards becomes difficult. This work can robustly assess the risk of derailment in operation for each train operating company situation, showing relationships of safety quantities with variables they can easily control. In particular, this work indicates that there might be the risk of vehicle derailment in some operation conditions, namely the risk of wheel unloading. Although vehicle speeds and loads may be the factors that would have a bigger effect on reducing wheel unloading, this work presents other variables of the wheel profile that also have influence on the vehicle safety and shows safe zones for profile parameters. Railway operators, restoring wheel profiles through maintenance actions, could keep wheel parameters within these zones. Therefore, keeping vehicles running with high speeds, loads and levels of safety.

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