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Robust adaptation of the train speed for energy saving under punctuality and security constraints

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Abstract:

Controlling energy consumption has turned to be an important challenge of the 21^{st} century and particularly in the railway world since the transport sector constitutes one of the largest consumers. For this reason, the railway companies pay close attention to their energy consumption and seek to reduce it. Recently, this objective has become even more crucial because of the growing demand stemming from the increase of the train frequency, as well as their speed. To achieve this consumption reduction, three levers can be activated: modify the rolling environment, the vehicle characteristics, or its speed profile. The present work focuses on the optimization of the speed profile. This latter must fulfill a number of constraints. First it has to respect the speed limitation on the track to assure the passengers' security; the involved constraints are called the *security constraints*. Second the train has to arrive in the train station at a certain time and a specific position with an appropriate speed; these are called the *punctuality constraints*. Third, the passengers should not be subjected to violent accelerations or jolts; these conditions are regrouped in the *comfort constraints*. Consequently, the mathematical problem consists in an optimization problem under *deterministic non-linear constraints*.

However, the speed profile is driven by the longitudinal behavior of the train on the track. The optimization supposes thus to construct a precise model to describe the train longitudinal dynamics and its energy consumption. But the mechanical system includes quantities that are more or less well known and variable: masses that depend on the ridership, aerodynamic loads and wheel-rail contact conditions that depend on the weather, stiffnesses and dampers that may be more or less damaged, etc. A probabilistic model is thus introduced to include the uncertainties inherent to the system. This modifies the cost function and the constraints, which become random variables and appropriate order relations need to be established. In this work we have also decided to optimize the driver commands rather than the speed trajectory. This should facilitate the implementation of the algorithms on autonomous trains. Finally the problem consists in optimizing the deterministic driver's command in order to minimize the mean value of the energy consumed, integrating the longitudinal dynamic behavior of the train, and respecting the set of probabilistic constraints (with a probability close to 1).

The approach adopted is therefore to build a model of the train's longitudinal dynamics (from a Lagrangian approach) and its energy consumption [1]. The train behavior is carefully modeled. Particular attention is paid to the definition of the traction, the pneumatic, and the dynamic braking capacities that can restore a part of the energy. Moreover, the track characteristics are introduced thanks to measured declivity and curvature and the amplitude and direction of the wind defined thanks to predictions of Meteo France, providing a good description of the train rolling environment. A modeling error is introduced including one term associated with the uncertainty in the longitudinal force and another in the energy consumed. This error sets the modeling in the probabilistic framework.

A sensitivity analysis is then carried out to identify the model parameters that have a large impact on the train dynamics and its energy consumption. The magnitude of the model error and the distribution

of the most important parameters are then estimated thanks to a *Bayesian formalism* [2]. The *a priori* distributions are built using the available physical knowledge (support, nominal values for the mean, the variance). The likelihood function is defined from a set of power and speed measurements performed on commercial trains (see [3] for details). Finally, the application of a Markov Chain Monte Carlo (MCMC) method, in particular the Metropolis-within-Gibbs algorithm [4], allows us to access to the *a posteriori* distributions that describe the uncertain parameters.

Ultimately, a *robust optimization* method under uncertainty is achieved to estimate the deterministic driver's command minimizing the mean value of the energy consumed. To do so, the Covariance Matrix Adaptation - Evolution Strategy (CMA-ES) algorithm [5] is used introducing the uncertainties as a form of noise applied to the cost function. The dynamic solutions that do not respect the safety constraints are directly rejected and an augmented Lagrangian penalization of the cost function is applied to introduce the punctuality and the comfort constraints.

The optimal speed trajectories are finally compared to the experimental traffic flow and the energy savings estimated are discussed.

This work presents several originalities. First of all, a special effort is made to ensure that the longitudinal dynamics model is representative. The errors are carefully modeled, and the parameters calibrated on a set of experimental measurements. This set of measurements also allows the comparison of the optimal solution with real journeys. Moreover the choice of the optimization variable is made on the driver's command and not to the train speed, as it is often the case in the literature, to facilitate the transposition of the developments to real systems. On the scientific point of view, this work has enabled the development of original methods to introduce non-linear constraints in a probabilistic framework thanks to order relations. Moreover, algorithms are developed for the robust optimization problem including uncertainties on both the objective function and the constraints.

References

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Short biography – Julien Nespoulous is currently an engineering PhD student at Gustave Eiffel University. He is supervised by Prof. Christian Soize, Prof. Guillaume Perrin and Dr. Christine Funfschilling. His thesis focuses on modeling the dynamics of high-speed train and optimizing train speed under constraints and uncertainty. The work is supported by the French railway company SNCF.