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A simulation-based optimization approach for the calibration of dynamic train speed profiles

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A B S T R A C T

Predictions of railway traffic are needed for the design of robust timetables and real-time traffic management. These tasks can be effectively performed only by using train running time models that reliably describe actual speed profiles. To this purpose calibration of model parameters against field data is a necessity. In this paper a simulation-based optimization approach is proposed to calibrate the parameters of the train dynamics equations from field data collected. Furthermore, a procedure for the estimation of train lengths has been developed. This method has been applied to trains with different rolling stock running on the Rotterdam–Delft corridor in the Netherlands. Probability distributions for each parameter are derived which can be used for simulation studies. The results show that the train length estimation model obtained good computation accuracy and the calibration method was effective in estimating the real train path trajectories. It has been observed that some of the parameters of tractive effort and resistance do not affect the train behaviour significantly. Also, the braking rate is significantly smoother than the default value used by the railway undertaking while calibrated resistance parameters tend to have lower mean than defaults. Finally, the computational efficiency of the approach is suitable for real-time applications.

Introduction

Recent demand growth for passenger and freight transportation in railway systems has raised the need for practitioners to increase the level of network capacity while keeping a high standard of service availability and quality. To achieve this aim railway traffic needs to be scheduled according to robust timetables that guarantee higher levels of capacity usage also in presence of stochastic disturbances. On the other hand, suitable control measures (e.g. train retiming, reordering and/or rerouting) must be applied in real-time by dispatchers to provide rescheduling plans that mitigate the effects of observed conflicts on network performances. Both robust timetabling and real-time management of railway traffic aim at supplying conflict-free train paths computed on the basis of off-line and on-line predictions of traffic behaviour. In the first step, train trajectories must be computed taking into account microscopic details of the infrastructure (e.g. lengths, gradients, curvatures of rail tracks, speed limits), signalling system (e.g. positions of signals, block section lengths, braking behaviour imposed by the automatic train protection), train composition (e.g. number of wagons, rolling stock characteristics), and current traffic information when the prediction is performed on-line. Then, based on the estimated train trajectory a conflict-free schedule is constructed by solving a mathematical problem (e.g. optimization, heuristics), or by relying on rule-of-thumbs or experience of the operator (i.e. a planner in timetabling and a dispatcher within real-time operations). The effectiveness of these schedules depends on the reliability of the estimated train trajectories and the precise identification of potential track conflicts. Inaccurate forecasts can lead to wrong detection of possible conflicts and to traffic schedules that are ineffective or even infeasible when put into operation. In this context, accurate traffic prediction models must be used to confidently describe the real evolution of train behaviour. To this purpose a proper calibration phase is needed to estimate input parameters against train data (e.g. position, speed) collected from the field, so that the model can reproduce the real train trajectories as much as possible.

This paper presents an approach to derive the most probable speed profiles of train runs from observed track occupation/release data. The train behaviour is modelled according to the Newton dynamic motion equations which are numerically integrated over distance employing the Runge–Kutta method (Butcher, 2003). A simulation-based optimization approach is adopted to calibrate input parameters of the equations describing the tractive effort, the motion resistances, the braking effort, and the cruising phase. These parameters are fine-tuned for different classes of train composition (defined by the number of wagons, the type of traction unit, and the length of the train) by minimizing the gap between observed and simulated running times, using a genetic algorithm. Additionally, since the train composition is not known with

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certainty beforehand, a model for train length estimation is developed. For each composition the calibration experiment is performed over a significant set of observed train runs. This enabled estimating the probability distributions the different input parameters for each class of train compositions. This aspect gives also insight in different driving behaviours adopted during real operations. The proposed approach is applied to train runs operating along the corridor Rotterdam–Delft in the Netherlands. Results illustrate the effectiveness of this method in calibrating parameters of the Newton's dynamic equations versus track occupation/release data collected at the level of track sections.

With this paper the authors provide the following main contributions:

- A novel simulation-based method to calibrate the parameters of the train dynamic motion equations against observed track occupation data. This approach allows the derivation of train speed profiles from the real distance–time trajectory collected at discrete points from track-free detection sections.
- A procedure to assess the length of trains from time to distance data collected by track-free detection sections
- A statistical assessment of parameters relative to both physical–mechanical characteristics of trains (e.g. coefficients of resistance and traction equations) and the behaviour of train drivers (e.g. compliance to the max speed limit on the track, braking rate applied).
- A practical application to a real test case which proves the applicability of the proposed approach and the usefulness that results can have for both practitioners (e.g. more reliable predictions of train trajectories) and academics (e.g. distribution of parameters suitable for robust timetabling design).

Section Literature review gives a literature review on the different approaches proposed to model train running times and calibrate model parameters. In Section Methodology, the methodology proposed in this paper is described. Section Case study: the Rotterdam-Delft corridor illustrates the case study considered for the application and provides the corresponding results. Conclusions and final comments are given in Section Conclusions.

Literature review

In the literature, several approaches are presented for estimating train running times taking into account microscopic features of both trains and the infrastructure (including the signalling system). In particular, models can be mainly divided in the ones using kinematic motion equations and others adopting a dynamic representation of the movement, basically by means of Newton''s motion formula (Hansen and Pachl, 2008).

Albrecht et al. (2006, 2010b) described train motion based on the kinematic equations and calibrate their parameters (speed and acceleration) versus track occupation data collected by means of train describer systems (Daamen et al., 2009; Goverde and Meng, 2011). Albrecht et al. (2010a) use calibrated kinematic models to understand the influence of the Dutch signalling and ATP system on train speed profile and energy consumption. The disadvantage of these models is that they calibrate only the parameters of the kinematic motion equations which are trajectory-dependent and cannot be used anymore when considering a different train run even if the rolling stock is the same.

Medeossi et al. (2011) use a dynamic equation for each phase of the train motion (i.e. acceleration, cruising, coasting and braking) and fine-tunes the respective performance parameters against GPS data collected on-board of the trains. A probability distribution is then estimated for these parameters to characterize stochastic variations of running times.

Hertel and Steckel (1992) proposed a model that computes running times based on theoretical stochastic distributions of train parameters (e.g. resistance coefficient, braking rate) instead of using typical deterministic parameters as commonly considered in practice. The parameter distributions adopted in this work are however not derived from any realised train run.

Kecman and Goverde (2013) adopt a method suitable for real-time predictions, that represents train trajectories by means of a weighted graph that evolves dynamically each time that new information is gathered from the field; weights of the arcs are train running and dwell times and minimum headway times measured by means of detailed track occupation/release data from train describer records collected at the level of track sections (e.g. axle counters, track circuits).

During real operations stochastic variations to individual train runs are observed due to changes in the rolling stock condition, rail deterioration, as well as variations in the train driver behaviour and weather circumstances. These unpredictable variations induce an alteration of train characteristics such as the deceleration and the acceleration rates as well as motion resistances (e.g. due to gradient, air viscosity, rail curvatures) and consequently, a change in train trajectories (Kecman and Goverde, 2013). According to this, approximated parameters estimated by manufacturer or train operators should not be taken for granted (Radosavljevic, 2006), but need to be computed for each train composition and railway corridor separately.

This work helps filling the gap between practice and theory under the following perspectives:

1. So far, research approaches proposed in literature were mainly focussed on calibrating parameters of the kinematic train motion equations (Albrecht et al., 2006, 2010a,b) or only performance factors of the dynamic train motion equations (Medeossi et al., 2011). This work instead has the objective to calibrate all the parameters of the dynamic train motion equation and not only performance factors as in Medeossi et al. (2011). The fact that we consider and calibrate all the parameters of the dynamic equation, gives to our model a higher flexibility than (Medeossi et al., 2011) since it can accurately describe every kind of observed trajectory. This means that it can reproduce every type of observed driving behaviour.
2. Compared to the previous work by Medeossi et al. (2011), the main advantage of our approach is that we manage to accurately describe observed train trajectories on the basis of track occupation data and not GPS. Currently, only in rare cases it is possible to use GPS data, given that the most part of railway networks in Europe are not equipped with these systems. Most part of the railway networks are equipped with track-free detection systems that detect the occupation/release of a certain track from a train. This means that the model proposed in this paper can be used for all those networks having track-free detection systems since we use exactly these data to calibrate train parameters. Moreover, these data are automatically collected which provides a big amount of data for detailed analyses.
3. The presented methodology provides probability distributions of train parameters fitted on data gathered from the real field, which can be used for more reliable robust timetabling (where train running times are generated from random distributions) or as more realistic input for the model of Hertel and Steckel (1992) to calculate train running times.

To the best of the authors' knowledge no efforts have been addressed in literature to the estimation of parameters relative to tractive effort and motion resistances based on actual track occupation data.