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Comparative analysis of algorithms and models for train running simulation

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In order to find an algorithm applicable for train running time simulation in timetabling and real-time control applications (conflict detection and resolution, driver advisory system), three state-of-the-art algorithms for running time computation are compared concerning calculation imprecisions and computation times which are the main requirements in those computations. Therefore the exact solution of the differential equation of movement of the infinitesimal calculus is compared with those of the numeric approximations by Euler's method and Gauss quadrature. A case study on German real-world tracks using three modern train configurations is performed. Additionally, the influences of mass modelling as mass strap or mass point and the possibility to emulate the mass strap behaviour by using a pre-computed slope profile is examined. Furthermore the influence of the detailedness of slope profiles on computation times and accuracy is analysed and a method which can be used for reducing the grade of detailedness of pre-computed slope profiles is shown. It is illustrated that high precision computations can only be carried out, when it is acceptable to use more computation time. In this context, the results reveal that this conflict of objectives can be solved by using a correctly parameterised Euler's method, which can be used for all applications under examination as it offers a good trade-off between calculation time and preciseness.

1. Introduction

1.1. Motivation

Since the early twentieth century, train running simulation has been a field of research in particular for timetabling, see (Brünger and Dahlhaus, 2011) for a short summary of the history. As timetabling is a very long process usually taking several months, there are no relevant computational requirements on running time simulation for this purpose. The obtained timetable which includes running time supplements represents a constraint for operation. Feedback from operation on a timetable is usually only given, if these constraints are not feasible during operation.

Today, train running simulation is also used for other related tasks, e.g. in

- dynamic traffic management algorithms to determine the consequences of dispatching decisions (e.g. delays of trains) also known as conflict detection and resolution, see Corman et al. (2011), D'Ariano et al. (2007), Rodriguez (2007), Wegele (2005) or Törnquist (2006) for an overview. This task has very high requirements on computation time, as usually many different train runs have to be computed in very short time.
- driver advisory systems for energy-efficient driving (DAS). They have high requirements on the accuracy of simulation results in order to actually achieve the desired effects of energy-saving and to obtain high user acceptance. As computations are usually carried out on mobile units with limited computational power, computational requirements are also significantly higher than for timetabling (see Albrecht, 2005; Howlett and Pudney, 1995; Kraft and Schnieder, 1981; Lüthi, 2009).

These real-time systems are used in the railways in order to improve operation quality by predicting or controlling railway traffic with a high precision. Therefore, they calculate internally with a time precision of usually 1 s (Albrecht, 2005; D'Ariano et al., 2007). Because errors, imprecisions or inconsistencies in train running simulation might lead to train path conflicts or delays in reality,

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these would not only contradict the original goals of the systems, but also create mistrust among the human operators like dispatchers, train drivers interacting with these systems.

The European research project ON-TIME (Optimal Networks for Train Integration Management in Europe (On-time project website, 2013)) aims at an integrated cascading control loop of railway operation, in which centralised traffic management systems are coupled with on-board driver advisory systems to further increase capacity (see Fig. 1).

It can be seen, that running time simulation plays a role at different process stages. As the timetabling process and both kinds of real-time systems shall work together seamlessly, a compatible train running simulation module is needed which fulfils both requirements of computation velocity and accuracy.

Unlike previous publications in the field, we try to systematically compare algorithms and models on real-world scenarios. The paper analyses different train and track models and the way, the differential equations of motion are solved for some reasonable combinations of them. Computational experiments are carried out to measure computation time and quantitative differences between the results, in particular for times at defined positions (which are needed for the computation of blocking times in the dispatching process), but also for velocity and energy related differences.

1.2. Requirements

A train running simulation has to calculate different physical measures. For timetabling purposes, usually the minimal running time is simulated. Therefore, it must be assured that the train velocity never exceeds the maximal velocity and that the train stops at the planned locations. Earliest arrival times at stations and passing times at intermediate stations are also evaluated for planning purposes. Furthermore, blocking times (Pachl, 2008) – for example signal passing and section release times – need to be computed. DAS applications require additional timing and velocity information on places where velocities or driving regimes (acceleration, braking, coasting, cruising) change.

The traction energy consumption and the potential energy recuperation is needed for DAS applications in order to evaluate different driving styles. For timetabling or dispatching applications, it could also be of use to estimate the energy consumption of different timetables or dispatching decisions (see Albrecht, 2009). It should be noted that instantaneous power as needed by tools for the simulation of the electric power supply is not considered here.

To meet the requirements of both, dynamic traffic management systems and DAS, an algorithm for train running time calculation is needed, which delivers a good trade-off between precision and computation times. If no such algorithm is available different will be used for timetabling, prediction and real-time rescheduling which could lead to scheduled times which are inconsistent to times computed in prediction and might therefore lead to false positive or false negative conflict detection. Furthermore conflict solutions given by real-time rescheduling algorithms might not be drivable and therefore cause further conflicts. This could lead the rescheduling to be at least partly counterproductive.

2. Models

For train running simulation the behaviour of the train on the track has to be modelled properly. Thereby appropriate modelling enables several methods for computing this simulation.

The movement of a train is primarily affected by three forces, which are train running resistance F_R, track resistance F_H and propulsion force F_Z which can be modelled in different ways.

2.1. Train running resistance model

The most important part of the running resistance, which works against the movement of vehicles is air resistance which is quadratically dependent on train velocity and also depends on wind force and direction. Rolling resistances e.g. caused by friction between bearings and axle or wheel rim and rail also occur. There are different models for both categories, which are explained in detail in Brünger and Dahlhaus (2011), Rochard and Schmid (2000) and Wende (2003). It is commonly agreed that all running resistances can be summarised with the Davis-formula and be modelled as polynomial with three parameters $c_0,\ c_1,\ \tilde{c}_2$ and train mass m

$$F_R = \tilde{c}_2 v^2 + m(c_1 v + c_0) \quad (1)$$

$$= m(c_2 v^2 + c_1 v + c_0). \quad (2)$$

Air resistance, which is modelled with parameter $\tilde{c}_2$, does not depend on the train mass but for computational reasons it is modelled as mass dependent coefficient $c_2 = \frac{\tilde{c}_2}{m}$. Therefore, the original non-dependent parameter is divided by the train mass. It should also be noted that the parameters c_2 and c_1 depend on wind velocity and, therefore, vary with different wind directions and forces encountered during a train run, but will be regarded as constant for this study.

2.2. Tractive effort model

The tractive effort of an electric vehicle at low velocity is limited by the maximal slip between wheel and rail which follows a shifted hyperbolic in dependence on train velocity (see Wende, 2003). Beyond a changeover velocity the tractive effort is inversely proportional to the train velocity and thus hyperbolic as well. To find a usable description of the tractive effort a compact presentation which provides the information as exact as possible is needed. The theoretic exact (shifted) hyperbolic traction force function $F_{hyperbolic}(v) = \frac{P}{v - v_0}$ (P constant power, v_0 shifting parameter) would fulfil these requirements, but in most cases tractive effort data is only given as a set of velocity-tractive-effort points. Moreover with

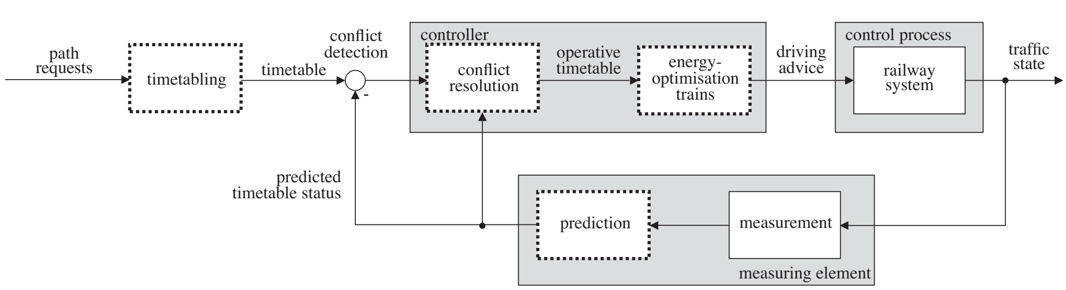

Fig. 1. System graph; bold dotted boxes: blocks with use of running time calculation.

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