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Railway line capacity consumption of different railway signalling systems under scheduled and disturbed conditions ☆

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ABSTRACT

This paper proposes the new concept of dynamic infrastructure occupation to assess infrastructure capacity under disturbed conditions as a complement to the established capacity indicator of scheduled infrastructure occupation. This new indicator is applied in a capacity assessment study of a Dutch railway corridor with different signalling configurations under both scheduled and disturbed traffic conditions. For scheduled conditions the standard UIC compression method for computing infrastructure occupation is used, while dynamic infrastructure occupation under disturbed conditions requires a Monte Carlo simulation set up. For the analysis we use the train dispatching system ROMA that combines the alternative graph formulation of train rescheduling with blocking time modelling of signalling constraints. For the disturbed conditions, four traffic control scenarios are considered: three heuristics and an advanced branch-and-bound algorithm. The results show that the scheduled infrastructure occupation with ETCS Level 2 significantly improves over the legacy Dutch NS'54/ATB. In delayed operations, there is a considerable gain for ETCS in terms of dynamic infrastructure occupation and punctuality compared to NS'54/ATB, since the braking distances decrease when delayed trains run at lower speeds, having a stabilizing effect on headway times, delay propagation and throughput.

1. Introduction

The characteristics of a signalling and automatic train protection (ATP) system have a significant impact on the capacity and stability of a railway line. One way to improve railway infrastructure capacity is to update the signalling or ATP system to one that allows a closer headway between successive trains. A capacity assessment with respect to the different signalling and ATP variants then reveals how much capacity gains can be achieved. In Europe, the new state-of-the-art European Train Control System (ETCS) has been implemented successfully on various new (high-speed) lines and moreover it is being implemented on six international freight corridors as decreed by the European Commission (EC) to improve interoperability of the European railways (Winter, 2009). In 2007, all European Union member states also had to submit a national implementation plan to the EC. The European countries are facing the strategic dilemma to how, where, and when to install ETCS on conventional railway lines. Different countries might have different reasons for replacing their safety and signalling systems, including interoperability, improved safety, increased capacity, replacing legacy systems at the end of their life cycle, and improved or extra functionality like higher supervised speeds. Since the investments of signalling equipment replacements are considerable, both in the infrastructure and rolling stock, a Social Cost-Benefit Analysis (SCBA) is typically applied to balance the costs to benefits. A crucial element in such analysis is the quantification of benefits (Invensys Rail Group (IRG), 2007; Transport Research Laboratory (TRL), 2010). This paper focuses on the evaluation of capacity benefits when implementing ETCS by comparing it with the legacy system for a case study in the Netherlands. Part of this study was performed in commission of the Dutch Parliament (Goverde et al., 2012).

The capacity consumption of a railway line can be calculated using the timetable compression method for given infrastructure characteristics, rolling stock characteristics and timetable pattern. This compression method is based on a deterministic microscopic calculation of conflict-free train paths with minimum headway times using blocking time theory (Hansen and Pachl, 2008). This approach is also adopted as the standard method for assessing capacity consumption by the International Union of Railways

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(UIC, 2004), which also gives empirically derived guidelines on the total required buffer time in a timetable pattern to be stable for delays. The UIC timetable compression method has been applied to evaluate the infrastructure occupation of various ETCS variants (UIC, 2008; UIC, 2010; Winter, 2009). In the literature, this capacity assessment method has been critically reviewed; see e.g. Landex (2009), Lindner (2011), and Lindner and Pachl (2010). For an overview of other capacity assessment methods, see Abril et al. (2008). Goverde (2007) complements the corridor-based microsopic capacity assessment with a network-based macroscopic stability analysis method that compresses the timetable while also taking dependencies between corridors into account. This network stability analysis approach has also been extended to a stochastic setting to evaluate the effect of stochastic process times on stability (Goverde et al., 2011).

Capacity assessment of railway systems is normally applied to scheduled train paths under fixed conditions. Recent capacity assessment works deal with advanced signalling systems (see e.g. Bartholomeus et al. (2011), Dingler et al. (2010), Lai and Wang (2013) and Winter (2009)), however, they do not consider the actual infrastructure occupation under disturbed conditions and typical statistical variations of operations. As a result, although theoretically conflict-free, a timetable could be very sensitive to train path deviations, even with a low (scheduled) infrastructure occupation (Medeossi et al., 2011). In the presence of delays, train path conflicts may occur depending on the scheduled buffer time between train paths. In practice this means that a train has to brake in response to the signalling system and possibly wait in rear of a stop signal. This leads to changed train trajectories with increased blocking times so that following trains may also be affected. The actual response to the signals depends on the specific signalling system and constraints of the ATP system, and can be quite different. In a standard three-aspect signalling system, trains have to brake from two signals in rear of an occupied block section to a restricted speed and continue with this restricted speed until a final brake before the red signal. In contrast, a cab signalling system as ETCS allows a train to proceed until an approach indication point that is determined by a dynamically computed braking curve on-board. This braking curve depends on the actual train speed and braking characteristics as well as on the infrastructure description until the end of the movement authority, such as gradients and local speed restrictions. Also the time of re-acceleration after an improved signal aspect depends on the (intermittent or continuous) ATP system.

The main contribution of this paper is the concept of *dynamic infrastructure occupation* that extends the UIC concept of (scheduled) infrastructure occupation to take into account stochastic delays, dynamic responses to the signalling system, and typical traffic control actions to deal with conflicts. The resulting train paths deviate from the scheduled ones and thus also the actual infrastructure occupation changes. This paper compares the infrastructure occupation both under scheduled and disturbed conditions. For the scheduled condition the standard UIC compression method is used; while for the disturbed conditions, we present the new concept of dynamic infrastructure occupation. Random distributions of initial delays are evaluated for each train when entering the corridor, which model the unavoidable variability of real-life operations. The resulting conflicts between trains are then detected and solved for multiple simulation runs. In each run, a *dynamic minimum cycle time* is computed, while the average infrastructure occupation of all replications is used as a measure of the (dynamic) infrastructure occupation for disturbed situations. Note that dynamic evaluations depend on the (time allowances in a) given timetable, the assumed delay distributions, and the train and traffic control applied. The influence of the dispatching process can be quite relevant in practice and the results derived from simple delay propagation tools (that keep the timetable order) or simple simulation (mostly based on some variation of the First-Come-First-Served rule) can be quite far from the real performance attainable by optimized traffic management systems.

For the capacity assessment we adopted the train dispatching system ROMA (Railway traffic Optimization by Means of Alternative graphs) (D'Ariano and Pranzo, 2009). ROMA is based on the combination of the alternative graph model (Mascis and Pacciarelli, 2002) and blocking time theory (Hansen and Pachl, 2008), and is thus applicable to any signalling/ATP system. For this study, ROMA is extended with various signalling/ATP systems so that the braking behaviour of hindered trains is simulated properly in the different configurations. Also the route-locking sectional-release principle is taken into account for accurate blocking time calculations in station areas (Corman et al., 2009). ROMA has been adapted in order to compute the compressed timetable with conflict-free train paths without and with rescheduling. For the calculation of the infrastructure occupation for disturbed scenarios with rescheduling, ROMA is applied in a Monte Carlo simulation set up. We use four traffic control approaches: keeping the scheduled order, a First-Come First-Served (FCFS) rule and a First-Leave First-Served (FLFS) rule, that are heuristic practical dispatching rules, and an advanced branch-and-bound (B&B) algorithm for optimal train scheduling (D'Ariano et al., 2007). The optimization approach was first developed in a software, named AGLIBRARY, for solving general scheduling and rerouting problems and then incorporated in ROMA. We evaluate the two capacity assessment approaches to demonstrate the potential advantage of real-time intelligent traffic control in combination with the ERTMS Level 2 two-way communication architecture.

The capacity assessment is applied in a case study of the Dutch Utrecht–Den Bosch corridor for different signalling/ATP systems. Four signalling/ATP system variants are considered: the current Dutch NS'54 speed signalling system with ATB train protection, the NS'54/ATB system but with optimized blocks near the stops, ETCS Level 2 with current block lengths, and ETCS Level 2 with shorter blocks. The disturbances are modelled as stochastic initial delays for all trains with train-type dependent distributions given by three-parameter Weibull distributions fitted by empirical data.

The next section explains the considered signalling and ATP systems, and the timetable compression method applied to these different systems. Section 3 explains the ROMA system and the extensions that we developed for modelling the signalling and ATP systems. Section 4 presents the new method for computing infrastructure occupation for both scheduled and disturbed conditions based on the alternative graph model used in this work. Section 5 illustrates the results to a practical case study regarding the Utrecht–Den Bosch corridor and discussed recommendations for practical implementation. Section 6 gives the conclusions of this paper.

2. Railway signalling and capacity consumption

2.1. Signalling and ATP systems

Railway safety systems can be partitioned in four components (Theeg and Vlasenko, 2009):

1. Track-free detection: detecting the occupation and release of track sections.
2. Interlocking: setting technically protected routes for safe train movements.
3. Signalling: indicating a movement authority to train drivers, and
4. Automatic train protection (ATP): guard against driver errors.