Real-time railway traffic management with demand prediction: formulation and solution approach

B. Pascariu[1] J. V. Flensburg[2] P. Pellegrini[1] C. M. L. Azevedo[3]

[1] Univertsité Gustave Eiffel, COSYS-ESTAS, F-59650 Villeneuve d'Ascq, France
{bianca.pascariu,paola.pellegrini}@univ-eiffel.fr

[2] Banedanmark, Traffic Division, 4100 Ringsted, Denmark {jvfl}@bane.dk

[3] Technical University of Denmark, Department of Technology, Management, and Economics, 2800 Kongens Lyngby, Denmark
{climaz}@dtu.dk

Keywords : *Real-time Railway Traffic Management; Passenger Demand Prediction; Mixed Integer Linear Programming*

Recent transport policies increasingly promote shifts towards rail travel aiming at a more sustainable transportation system. This shift is hampered by widespread unexpected disturbances in operations, resulting in perceived poor punctuality and reliability. When prevention of such perturbations is not feasible, the infrastructure manager must mitigate their effects, resolving arising conflicts to restore regular train operations and minimize delay. The problem faced by infrastructure managers to deal with everyday perturbations is known in the literature as the real-time Railway Traffic Management Problem (rtRTMP) [1]. The goal of the rtRTMP is to reduce delay propagation, with as little inconvenience to operators and passengers as possible. Current practice generally includes the assessment of railway performance in terms of train delays, but the quality of service to passengers is rarely explicitly accounted for [2]. We propose a railway traffic management framework that accounts for both passenger and train delays. To do so, we propose a predictive optimization framework.

The novel framework involves the interaction of a demand prediction, a demand assignment, and a traffic management modules, as follows. First, a short-term traffic state prediction (TSP) is computed for a pre-defined control area within a given time horizon. This prediction assumes that the currently implemented real-time traffic plan (RTTP) will be executed. In parallel, based on the observed demand, the origin-destination (OD) demand prediction module produces an OD matrix that represents passenger flow within a specified time frame through the application of linear regression. Then, the demand assignment module identifies the expected train-based paths passengers will choose and outputs a passenger assignment plan (PAP). A train-based path is a sequence of trains that can be used for an OD pair and any associated connections. The PAP reports the expected number of passengers traveling between each pair of origin and destination stations per train-based path, along with the desired arrival times at the destination.

The TSP and the PAP are then used in the traffic management module to solve the rtRTMP, where the general objective function based on train delays [1] is extended with passenger delays at destination. For this third module, we integrate passenger modeling in the state-of-the-art rtRTMP solver called RECIFE-MILP [1]: we account for passenger connections to allow the execution of train-based paths as defined in the PAP. The output is the final RTTP to be implemented until the next application of the framework.

We consider demand as dynamic data, i.e., we reckon that passenger behavior is at least partially driven by traffic conditions. Iterations between the traffic management and the demand assignment modules concretize this dynamic redistribution of passenger demand: passenger delay is assessed based on a passenger assignment that reflects traffic conditions, which are in turn defined by traffic management decisions.

Based on this framework, we evaluate three solution approaches. They represent different interactions between prediction and optimization:

- *PaxHard:* The traffic management module includes demand estimates in its formulation and sets hard constraints for passenger connections to ensure the transfers in the PAP;
- *PaxSoft:* The traffic management module includes demand estimates in its formulation and sets soft constraints for the passenger connections. They are introduced with penalties in the objective function, for each broken PAP transfer. Penalties are proportional to the planned headway of the receiving service;
- *PaxSoftMulti:* The traffic management module uses soft constraints similar to *PaxSoft*. Here, to account for passengers reacting to changes in the traffic plan, the optimizer generates multiple RTTPs. For each RTTP, the demand assignment produces a separate PAP, based on the predicted demand. Thus, each RTTP is evaluated with the corresponding PAP, and the best one is chosen.

We extensively assess our framework and each solution approach on the Copenhagen suburban railway network. We evaluate our proposed OD demand prediction model against a weekly historical average model and benchmark our approaches against the application of timetable routes and orders, and the passenger-agnostic RECIFE-MILP. We consider instances representing traffic evolution within an hour, with passengers entering the system in the first 20 minutes. For the assessment, we evaluate performance indicators related to train and passenger travel times and delays, considering the real observed demand.

The results show that explicitly accounting for passengers in decision making effectively guides traffic management toward the reduction of passenger delays without remarkably penalizing trains, compared to the classic railway traffic management policy. Indeed, PaxHard, PaxSoft and PaxSoftMulti reduce passenger delays with only a small increase in train delays compared to passenger-agnostic solutions. This outcome derives from prioritizing trains with more passengers and better managing transfer options.

Comparing the solution approaches, the results show that hard constraints for passenger transfers can hinder performance when few passengers are involved. Instead, soft constraints are better as they allow for an evaluation of the delays derived from whether or not a transfer is preserved. Moreover, PaxSoftMulti leads to the best solutions thanks to the consideration of the dynamic redistribution of passenger demand in response to different possible traffic configurations.

Acknowledgements

This work is part of SORTEDMOBILITY project, which is supported by the European Commission and funded under the Horizon 2020 ERA-NET Cofund scheme under grant agreement N. 875022.

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