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Integrated modeling of high performance passenger and freight train planning on shared-use corridors in the US

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ABSTRACT

This paper studies strategic level train planning for high performance passenger and freight train operations on shared-use corridors in the US. We develop a hypergraph-based, two-level approach to sequentially minimize passenger and freight costs while scheduling train services. Passenger schedule delay and freight lost demand are explicitly modeled. We explore different solution strategies and conclude that a problem-tailored linearized reformulation yields superior computational performance. Using realistic parameter values, our numerical experiments show that passenger cost due to schedule delay is comparable to in-vehicle travel time cost and rail fare. In most cases, marginal freight cost increase from scheduling more passenger trains is higher than marginal reduction in passenger schedule delay cost. The heterogeneity of train speed reduces the number of freight trains that can run on a corridor. Greater tolerance for delays could reduce lost demand and overall cost on the freight side. The approach developed in the paper could be applied to other scenarios with different parameter values.
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1. Introduction

Passenger rail has been resurging in the US. Amtrak, the primary intercity rail service provider, has witnessed 51.1% ridership growth between 2000 and 2013, from 20.9 to 31.6 million passengers (Amtrak, 2013). To sustain this trend and promote sustainability and multimodality for inter-city travel, several states have been pursuing high performance rail systems. Among many, California has started building a $68 billion brand-new, dedicated High Speed Rail (HSR) line (California HSR, 2012). The Midwest region takes a more conservative approach by taking advantage of using existing rail infrastructure by both passenger and freight trains (Peterman et al., 2009). One prominent example is the Chicago-St. Louis corridor, where the existing single-track line owned by Union Pacific railroad is being upgraded to accommodate future passenger services running at up to 110 mph. Once track upgrade is completed in 2017, the travel time between Chicago and St Louis will be reduced by 1 h (Illinois HSR, 2014). By utilizing existing infrastructure, the project cost is much lower than California HSR, only a few billion dollars for the initial phase (Illinois HSR, 2014). Given the economic appeal of high performance passenger rail on shared-use corridors and the fact that such services have not been put in place, it is important to understand, from the strategic planning perspective, the interactions between passenger and freight services.

Strategic planning on shared-use corridors has different meanings for passenger and freight trains. On the passenger side, strategic planning pertains to determining preliminary, non-minute-by-minute train schedules given passenger demand and the number of trains. It is part of the scheduling stage of a typical six-stage rail planning process (Ghoseiri et al., 2004). On the

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freight side, strategic level planning refers to modeling train operations taking account of overall freight demand and the number of programmed services, without going into detailed operating characteristics. This is of particular relevance in the US, where freight train departures are a function of demand: a train simply departs once it receives sufficient load (Cordeau et al., 1998).

Because Amtrak is a publically funded entity, we assume in this study that Amtrak cares about passenger benefits. One important measure related to passenger benefits is passenger schedule delay. For a passenger, schedule delay is the time difference between one's preferred and actual departure (Hendrickson and Kocur, 1981), which characterizes the inconvenience of transportation service schedule to accommodate one's desired activities. In passenger rail service planning, very limited attention has been paid to schedule delay. For non-rail modes, Kanafani (1983) shows that in case of air passenger transportation, cost due to schedule delay is comparable to other cost components in short-haul markets. Given that train services are typically less frequent than flights in the US, we expect schedule delay plays an even more important role in planning passenger rail services.

Quantifying passenger schedule delay requires knowledge about both the departure time of trains and the distribution of passenger preferred departure time (PDT). Modern travel survey methods, travel demand forecasting techniques, and automated passenger counting systems have made possible constructing distribution profiles of passenger PDTs, in which PDTs are discretized into relatively coarse time intervals (e.g., 15-min intervals as in Cascetta and Coppola (2012)). For consistency, it is sensible to consider train schedules with similar time resolution.

The objective of the paper is to investigate strategic level rail planning on shared-use corridors with the presence of high performance passenger trains. We recognize that, by the US Federal law (110 Congress, 2008; Harrod, 2009; Wilner, 2013), passenger trains are given access priority over freight operations on shared-use corridors. We employ a hypergraph-based, two-level nonlinear integer programming model to sequentially determine passenger and freight train schedules. This depicts the scenario in which the federal law is effectively applied. Passenger schedule delay and lost freight demand due to infrastructure capacity constraints are explicitly incorporated in the modeling process. By exploring different solution strategies, we conclude that a problem-tailored linearized reformulation of the original model yields superior computational performance. Using realistic parameter values, our numerical experiments show that passenger cost due to schedule delay is comparable to in-vehicle travel time cost and rail fare. We find that in most cases marginal freight cost increase from scheduling more passenger trains is higher than marginal reduction in passenger schedule delay cost. The heterogeneity of train speed reduces the number of freight trains that can run on a shared-use corridor. Greater tolerance for delays of the freight operator could reduce lost demand and overall freight side cost. The approach developed in the paper could be applied to other scenarios with different parameter values.

We begin with a review of train scheduling literature in Section 2. The mathematical formulation of our problem is presented in Section 3. We discuss on the solution strategies in Section 4. Section 5 performs numerical analyses, on both a sample problem and a simplified case study for the Chicago-St Louis HSR corridor. Sensitivity analysis on speed heterogeneity and freight train delay tolerance are also conducted. Section 6 summarizes major findings and offers directions for future research.

2. Literature review and research contribution

The research on train scheduling dates back to as early as Frank (1966). Models developed since then fall into three categories: analytical, simulation, and discrete optimization approaches (Abril et al., 2008). The analytical approach uses simple models to estimate rail line capacity, train delay, and cycle times through probabilistic or deterministic analysis of train dispatching patterns (e.g., Chen and Harker, 1990; Hallowell and Harker, 1996; Flier et al., 2009). However, the simplicity of this approach limits its capability in dealing with complex real world situations.

Simulation is the dominant method in practice. Commercial software such as Rail Traffic Controller (RTC) (Willson, 2012) and Módulo Optimizador de Mallas (MOM) (Barber et al., 2006) incorporate a range of parameters, including train types, equipment types, terrain and track conditions, train speed, acceleration and deceleration, and traffic signals, to reflect train dispatching and operation in the real world. In general, the simulation approach does not seek to optimize train schedules, unless combined with optimization techniques (e.g., Jovanović and Harker, 1991). In addition, passenger cost is not considered while simulating train schedules.

The discrete optimization approach uses mathematical programming to identify train schedules that correspond to user-defined system optimum in fairly complex situations. Under this approach, train scheduling is most commonly modeled with discrete time networks, multi-commodity flows, and constrained resources. Since the first study by Amit and Goldfarb (1971), the literature has grown substantially. We review below only some of the more recent papers that are relevant to our study. Carey and Lockwood (1995) formulate a 0-1 mixed integer program for train dispatching on a single uni-directional line where overtaking is allowed. The objective is to minimize total cost which is the sum of cost of deviating from preferred departure and arrival; cost of travel times on links; and cost of dwell times at stations. To solve large-scale problems, the authors propose an iterative decomposition approach that is analogous to manual search strategies which human train planners found very effective in practice. The research is extended to more general networks with choice of lines, platforms, and routes (Carey, 1994a), and two-way track (1994b). Brännlund et al. (1998) present a binary linear program for scheduling passenger and freight trains on a single-track corridor. The objective is to maximize profits of all trains subject to track capacity constraints. Using Lagrangian relaxation, the original problem is decomposed into independent shortest path subproblems, one for each train. Caprara et al. (2002, 2006) seek train timetables with least deviation from the *ideal* ones, given track capacity constraints. Binary linear

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