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Disruption risk management in railroad networks: An optimization-based methodology and a case study

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ABSTRACT

We propose an optimization-based methodology for recovery from random disruptions in service legs and train services in a railroad network. A network optimization model is solved for each service leg to evaluate a number of what-if scenarios. The solutions of these optimization problems are then used in a predictive model to identify the critical disruption factors and accordingly design a suitable mitigation strategy. A mitigation strategy, such as adding flexible or redundant capacity in the network, is an action that is deliberately taken by management in order to hedge against the cost and impact of disruption if it occurs. It is important that managers consider the trade-offs between the cost of mitigation strategy and the expected cost of disruption. The proposed methodology is applied to a case study built using the realistic infrastructure of a railroad network in the mid-west United States. The resulting analysis underscores the importance of accepting a slight increase in pre-disruption transportation costs, which in turn will enhance network resiliency by building dis-similar paths for train services, and by installing alternative links around critical service legs.

1. Introduction

Freight railroads, an indispensable part of the North American transportation system, serve nearly every industrial, wholesale, retail, and resource-based sector of the economy. Based on the latest available statistics, railroads shipped over 1600 million tons of goods in the United States (DOT, 2013) and 336.5 million tons in Canada (TC, 2013). It is interesting to note that coordination among over 570 different freight railroad companies, who collectively own and manage the nearly 140,000-mile integrated network, ensure the smooth and efficient flow of freight (AAR, 2014). In light of the above, it is evident that sub-par operation resulting from either malfunctioning infrastructure or temporary track blockage because of an accident would not only have an unfavorable impact on the customer service but also an adverse effect on the economy. Such disruptions often necessitate rescheduling and/or rerouting of trains, and invariably result in delayed deliveries since their exact durations are unknown and difficult to anticipate.

It is interesting to note that disruptions to railroad operations, like those to business operations, are not infrequent (WS DOT, 2014; Stecke and Kumar, 2009). For example, sixty-one disruptions were registered for just the Seattle–Vancouver Amtrak operation between 2009 and 2013. Such disruptions could either lead to complete cancellation of train services (i.e., annulment) for a period of time, or to partial disruption of the train service where the train may be active over only a portion of the original route (i.e., a set of track segments between consecutive stops called service legs). Note that a train

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service is typically defined using the origin and destination yards, the route it will take along with the intermediate stops, the speed it will operate at, and the priority it is being assigned. Furthermore, in an effort to compensate for lost service, the disruptions typically result in increased utilization of the other network segments and/or deployment of other modes of transportation such as trucks. Our focus is on random disruptions to the tracks/ service legs of a freight railroad operator. Given the importance of a normally functioning network, and market competitiveness, it is not surprising that railroad companies (and appropriate government jurisdictions) are proactively planning for unforeseen disruption events. However, it is unlikely that such planning will completely eliminate all the sources of disruption, and hence it is important that railroad companies also have appropriate mitigation strategies and recovery plans to deal with disruptions. We aim to close that gap by proposing a decision framework that would answer the following questions: What optimal tactical measures can be adopted right after disruption so as to bring the network back to its normal status at the least cost possible? How do we design the railroad network so as to reduce the impact of future disruption? How can we measure the impact of mitigation strategies on potential railroad disruptions?

To that end, we propose a methodology to aid railroad companies make informed decisions in both pre- and post-disruption periods. More specifically, the proposed methodology combines optimization and predictive modeling. In the first stage, the optimization model is used to simulate the impact of various what-if scenarios, which are then analyzed to predict the critical factors in the given network, and to develop appropriate mitigation and recovery strategies to hedge against possible future disruptions. The proposed methodology was used to determine the critical links in the realistic railroad network in mid-west United States, and resulting analyses indicate that resiliency in supply chains can be significantly enhanced by developing mitigation strategies for critical links in the network, which often require minimal changes to the existing configuration. Finally, we note that the proposed methodology can also be used to provide emergency routes, similar to those for passengers (Corman et al., 2011), in the event of railroad disruptions.

The rest of the paper is organized as follows. Section 2 provides a comprehensive literature review, followed by the proposed methodology in Section 3. The pre- and post-disruption models are developed in Section 4, followed by the case study and the resulting analyses in Section 5. Finally, conclusion and directions of future research are discussed in Section 6.

2. Literature review

Rail transportation has presented a variety of rich problems that have been modeled and solved using mathematical optimization techniques since the 1950s (Beckmann et al., 1956). We invite the reader to refer to Cordeau et al. (1998) for an excellent review. Although the initial engagements in this domain were largely making use of simulation (Assad 1980; Haghani, 1987), deregulation of the industry coupled with increased computational power encouraged the use of mathematical optimization techniques to study a variety of problems spanning the entire spectrum of railroad operation (Barnhart et al., 2000; Ahuja et al., 2007; Verma et al., 2011). Evidently both the modeling effort and the resulting solution provided a set of recommendations for normal operating conditions, which would be infeasible if the freight network experience any form of unexpected disturbance or disruptions (Khaled et al., 2015). In railroads, minor incidents are called disturbances, while major incidents are called disruptions and require significant changes to the pre-set schedules (Nielsen et al., 2012). It is evident that both passenger and freight flows would be impacted as a result of disruption. We review the pertinent works from the passenger transportation domain because the majority of recovery models and algorithms have been developed in this space (Cacchiani et al., 2014). Finally, we note that despite the similarities between passenger and freight, it is often easier to monetize delays in the latter by developing appropriate clauses in the contract between the railroad operator and the customer, which we do in this paper.

The actual movement of trains in a network is based on a timetable, which is carried out by the assigned resources (i.e., locomotives, railcars, and crew). Though, in principle, the timetable and resource duties are conflict free, the real-time operations of a rail freight network is subject to disruptions (Kroon et al., 2009). Note that the post-disruption re-routing of traffic, typically on a reduced network, has to consider congestion and capacity (Khaled et al., 2015), and could require a change to timetable and resource assignment (Cacchiani et al., 2014). Though the focus on our work is on strategic/ tactical issues, we do review relevant works on resource assignment in railroad transportation.

The first group of studies focused on trip related details at a yard or track level, and describe a simulation procedure to determine the effectiveness of various recovery strategies (Wiklund, 2007), a model to determine the best point to stop obstructed trains so that unobstructed trains can still reach their destinations (Hirai et al., 2009), and the relative merits of a centralized versus distributed approaches for rescheduling (Corman et al., 2011). The second group assumed a more macro approach by focusing at the network level. To this end, Shimizu et al. (2008) proposed a constraint programming approach to minimize delay when an earthquake has damaged a section of the network, while Nakamura et al. (2011) and Louwerse and Huisman (2014) focused on post-disruption design and schedule of trains. Finally, Albrecht et al. (2013) consider the problem of disruptions due to track maintenance, while Narayanaswami and Rangaraj (2013) consider the problem of rescheduling multiple trains because of track blockage.

Note that disruption could render the original resource allocations infeasible, which has been a popular research area. Budai et al. (2010) studied the rebalancing problem in the event of disruption, while Nielsen et al. (2012) proposed a rolling horizon solution approach for real-time rescheduling of railcars and crews with application to passenger transportation, which was extended to incorporate dynamic passenger flow information in Kroon et al. (2015). Lingaya et al. (2002)