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Stochastic seat allocation models for passenger rail transportation under customer choice

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ABSTRACT

We study the seat allocation problem for passenger rail revenue management, in which a rail operator attempts to determine the optimal quantity of seats to be allocated to each cabin class for each train service. We formulate the problem with single-stage and multi-stage decisions as two stochastic programming models that incorporate passengers' choice behavior. We transform the stochastic models into equivalent deterministic mathematical programs that are easy to solve. Then, we form a variety of seat allocation polices from the optimal solutions to the seat allocation models. A number of simulation tests are offered to test the policies.

1. Introduction

The past decade has witnessed an explosive growth of investment on rail infrastructures in Asia. For instance, more than 18,000 km of high-speed rail (HSR) roads have been added to the existing regular-speed rail (RSR) network in China. The China–Southeastern Asia High-speed Railway Network is also being established. In 2013, the Chinese government opened up a deregulated railway market and the Chinese Ministry of Railways established a firm – China Railway Corporation (CRC). The CRC owns 18 companies, each of which operates individual freight and passenger rail transportation businesses in a particular regional market.

We refer to a carrier that operates rail lines and offers rail services to passengers as a *rail operator*. The rail operator provides periodically repeated services to passengers, i.e., the same services offered during a *service period* will be provided for the service period right after it – like the flight services in the airline industry.

Product and resource. Consider a rail operator that sends a number of HSR trains and a number of RSR trains from a specific initial station to a specific terminal station during a specific service period, say a day. All the trains depart from the same initial station but with different departure times, possibly with each passing through a series of intermediate stations when running towards the terminal. Note that these trains do not have to stop at the same sequence of intermediate stations.

The rail operator sells tickets to passengers for both the HSR and RSR services. Each ticket specifies a bundle of information, including the origin (i.e., the departure station), destination (i.e., the arrival station), and *itinerary* that specifies the service line (e.g., HSR or RSR), departure time (e.g., 9:00 am, 11:00 am, or 2:00 pm), and cabin class (e.g., business, first, or

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economy). A *product* is referred to as an *origin-destination (OD) itinerary* combination. Each train may traverse a sequence of rail legs (i.e., the segments between two successive stations). A *resource* refers to the seats of a particular cabin class on a train with a particular departure time over a leg.

Fig. 1 shows an example of the rail operator's rail services, for which passengers could acquire various products, such as AB-HSR-9:00 am-first, AC-HSR-2:00 pm-business, and AC-RSR-11:00 pm-economy. Examples of resources include the first-class seats for the 9:00 am HSR train on AB, the economy-class seats for the 6:00 am HSR train on BC, the first-class seats for the 10:00 am RSR train on AB, and et cetera.

Revenue management. Since the quantity of resources (i.e., the seats) is capacity-constrained, it is of central interest to a rail operator to maximize her revenue by optimizing the use of the resources. As one of the widely used tools, revenue management could be used to maximize a rail operator's revenue in a railway market. Revenue management was initially introduced after the deregulation of the U.S. airline industry in 1970s (Ciancimino et al., 1999). Existing empirical applications have well demonstrated that revenue management plays an important role in transportation industries, such as the airline industry (Belobaba, 1987, 1989; Subramanian et al., 1999; Wright et al., 2010), shipping industry (Wang et al., 2015), and railway industry (Abe, 2007; Riss et al., 2008; Yuan et al., 2008; Armstrong and Meissner, 2010; Wang et al., 2012). For example, French National Railway Operator used a revenue management system to improve the yields of passenger transportation (Armstrong and Meissner, 2010).

Seat allocation techniques are typically utilized to manage the revenue of passenger rail transportation. Specifically, the rail operator needs to solve a seat allocation problem, in which the rail operator attempts to determine the number of seats to be allocated to each OD pair for each cabin class to maximize her total revenue. We show below that utilizing seat allocation techniques could be beneficial in practice.

A running example. As shown in Fig. 1, we consider a passenger transport market with only two trains: an HSR train and a RSR train each having only one cabin class. Both the lines are originated from A and destined for C and there exist three OD pairs: AB, BC, and AC. For each OD pair, passengers can freely take any one of two rail lines. The rail operator offers tickets subject to limited capacities of rail lines. Suppose that the HSR line has 100 seats and RSR line has a capacity of 200 seats. The passenger demands and ticket prices are given in Table 1.

The rail operator determines how many seats to be assigned for each OD pair. It turns out different seat assignment policies produce quite different amounts of revenue from the rail operator's point of view. Assume that a passenger will choose the cheaper one between the HSR and RSR if both of them have seats available. We consider the following three cases of seat allocation, as shown in Table 2.

- Case 1. The RSR preserves 100 seats for each of AC, AB, and BC, while the HSR allocates its whole 100 seats to each of AB and BC but has no seats allocated to AC. Under this case, all customers will choose the RSR, leading to a total revenue of $100 \times 10 + 100 \times 20 + 100 \times 10 = 4000$.
- Case 2. The RSR allocates 100 seats to AC and has no seats for AB or BC, while the HSR allocates 100 seats for each of AB and BC, but closes to customers who request seats for AC. The total revenue is computed as 20×100 (for AC) $+ 20 \times 100$ (for AB) $+ 20 \times 100$ (for BC) $= 6000$.
- Case 3. The HSR allocates 50 seats to each of OD pairs, AB, BC, and AC, and the RSR does the same. Thus, the rail operator earns $50 \times 10 + 50 \times 20 + 50 \times 10 = 2000$ from the RSR and $50 \times 20 + 50 \times 40 + 50 \times 20 = 4000$ from the HSR, which gives 6000 in total.

This simple example clearly shows the value of seat allocation. The rail operator would probably adopt the policy under Case 2 or Case 3, which generates 2000 more in revenue than Case 1 does.

A real railway market would be more complicated. First, network effects exist in the sense that several products may share a common resource, causing that selling one product reduces the seat inventories of all other itineraries that consume the same resource. As we see from Fig. 1, AC and AB share leg AB, while AC and BC share leg BC.

Second, for air flights, tickets are sold for business and economy cabins. For passenger trains, passengers need to make a nested choice, called the "line-first-cabin-second" choice, i.e., a passenger first chooses between the HSR and RSR, and then, decide which cabin class to select. The nested choice is one of the features that distinguishes passenger rail transportation from the airline industry.

Third, in addition to the network effects and nested choice, we have to address the impact of demand uncertainties in the railway market. Passengers' ticket booking requests always come in random. This leads to a challenging problem, since

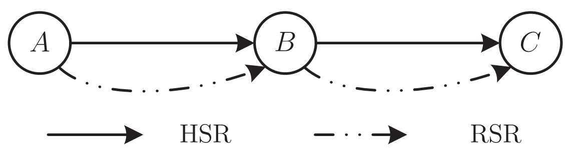

Fig. 1. An illustrative example.