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RESEARCH PAPER

Modeling Optimal Fare and Service Provisions for a Crowded Rail Transit Line

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Abstract: To relieve worsening traffic congestion and protect the deteriorating environment, many cities in China start to operate rail transit lines. However, the expected modal shift will only occur if the rail transit system offers great advantages over road transport modes. To this end, designing efficient operational arrangement has far-reaching impacts not only on rail transit itself, but also on the overall urban transport system. Focusing on a crowded rail transit line, this paper aims to jointly optimize fare, frequency and number of carriages under advocated management objectives. Factors that enter into this joint optimization include negative externality arising from noise pollution, the adverse effect from in-vehicle crowding and positive externality from road congestion relief. To assess whether the rail transit line in a given corridor is priced efficiently and the service provision is appropriate, detailed numerical calculations are carried out for one representative Chinese city---Suzhou. A synthesis of theoretical and empirical analyses depicts: compared with profit optima, social welfare optima are characterized with lower fares, greater frequency, more number of carriages and higher ridership; the change from the current operational arrangement to social optimum would call for reducing fares, increasing frequency and adopting more carriages.

Key Words: urban traffic; optimal service provisions; analytical optimization modeling; rail transit services; in-vehicle crowding cost functions

1 Introduction

Over the last decade urban scale and car ownership are both on a substantial growth, leading to increasing traffic congestion and environmental pollution. To help alleviate congestion and protect the environment, the enthusiasm for constructing rail transit lines is booming in China. In the end of 2008, 11 cities had rail transit lines in operation. However, the expected modal shift toward rail transit will only occur if it can offer great advantages over its competing modes. Thus, designing an efficient operational scheme has far-reaching impacts not only on the transit line itself, but also on the overall urban transport system.

In the strategic and tactical planning, fare, frequency and number of carriages are three key design variables[1]. Irrespective of ownership, most rail transit operators in China set fares roughly to cover a fixed percentage of total costs and determine frequency according to the rule of thumb of "maximum section load". Obviously, these decision rules fail to make resources reach Pareto Optimality. To determine what "optimal operational configuration" would look like, we jointly optimize fares, frequency and number of carriages under alternative management objectives by taking some relevant "externalities," such as in-vehicle crowding, congestion-relief benefit and noise pollution into consideration.

The rest of the paper is structured as follows: in Section 2, an in-depth literature review on optimal operation design is presented from two distinct strains. In Section 3, having taken both positive externality and negative externality into account, micro-economic models for profit and social welfare maximization are presented to provide explicit decision rules for fares, frequency, and number of carriages. Furthermore, the comparative static analysis (CSA) is employed to compare the relative order of magnitude between social welfare optima and profit optima. In Section 4, we conduct a detailed

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numerical case study for Suzhou rail transit line 1 to assess its current operating scheme. Finally, the major findings are summarized in Section 5.

2 Literature review

As a response to the substantial change of the urban transport environment, a large body of researches has been increasing over several decades. Particularly, after the appearance of the seminal paper written by Vickrey[2], numerous efforts have been made from two distinct strains in urban transportation economies.

The first strain directly concerns minimizing "total system costs". Assuming the demand is inelastic, it involves a trade-off between two types of resources: those provided by operators and those contributed by passengers—namely their time. This approach was first addressed by Mohring[3,4] and has been extended to include more factors by Jansson *et al*.[5–8] and recently by Jara-Díaz *et al*.[9–11]. Specific contributions for each paper in this stream are presented in Table 1.

In the last decades, although this approach has provided a good guide to improve transit operations, a minor drawback can be easily detected, namely, the approach is merely

Table 1 Literatures of minimizing total system costs for inelastic demand

Authors	Research objective	Policy variables	Objective function	Operating cost function	Externality	Approach
Mohring (1972)	Urban bus	Frequency Bus stops	Min. system cost	Linear with veh-hour	None	AMM[a]
Jansson (1979)	Scheduled service	Fare	Min. social cost	Linear with veh-hour	None	AMM
Jansson (1980)	Scheduled service	Frequency Bus size	Min. social cost	Linear with veh-hour, veh-km and peak vehicles	None	AMM
Viton (1983)	Highway and bus	Service level Bus fare Road toll	Min. total costs Max. net benefit	Linear with bus-mile and bus-hour	None	CSM[b]
Kraus (1991)	Mass transit	Marginal costs Fare	Min. Total system cost	Linear with veh-hour	In-vehicle crowding	AMM
Chang and Schindeld (1991)	Urban bus	Frequency Line density	Min. total system cost	Linear with veh-hour and veh-km	None	AMM
Jara-Díaz (2003)	Urban bus system	Frequency Fleet Vehicle size	Min. total value of resource	Linear with vehicle and vehicle size	In-vehicle crowding	AMM
Small (2004)	Highway and urban bus	Frequency Routes	Min. total system cost	Linear with bus-hour and bus size	None	CSM
Tirachini and Hensher (2009)	Urban public transit	Frequency	Min. total cost	Linear with veh-km, veh-hour and running kilometer	None	AMM

Note: a: AMM stands for the analytical mathematical method; b: CSM denotes the computer simulation method.

Table 2 Literatures of maximizing social welfare for elastic demand

Authors	Research Objectives	Optimal variables	Objective Function	Operating cost function	Externality	Approach
Nash (1978)	Urban bus	Frequency fares	Max. social welfare, profit, ridership and bus miles	Linear with bus-mile	None	AMM
Viton (1980)	Express bus service	Headway routes fare	Max. operator profit	Liner with bus-hour and bus-mile	None	AMM
Larsen (1983)	Schedule passenger transport	Fare	Max. social net income	Linear with vehicle-mile and passenger-mile	None	AMM
Else (1985)	Scheduled transport services	Fare service level load factor	Max. Social net benefit	Linear with ridership and level of service	Crowding, congestion, pollution, accident	AMM
Oldfield and Bly (1988)	Urban bus	Fare service level bus size	Max. net benefit	Linear with bus size	Congestion	AMM CSM
Jansson (1993)	Schedule passenger transport	Fare frequency	Max. social welfare	Linear with vehicle-hour and vehicle-km	None	AMM
Evans and Morrison (1997)	Urban transit	Fare service level passenger risk	Max. net benefit	Linear with service level	Accident risk	AMM
Jansson (2008)	Rail Passenger service	Fare frequency number of carriages	Max. social welfare Max. operator profit	Linear with veh-km, vehicle size and number of passengers	In-vehicle crowding	AMM