Optimization of Public Transportation Systems in Suburban Urban Areas
-Development and Application of a Model
for Simultaneous Determination of Network Structure, Traffic Volume and Fares

ABSTRACT :

Demand for bus systems has been declining for a long time due to the spread of private cars, changing lifestyles, and population decline. Particularly after 2020, the number of public transportation users declined significantly due to the COVID-19 pandemic. Much of the research on regional public transportation has focused on the more hard-pressed rural areas. However, bus services have frequently been reduced or downsized in recent years, even in metropolitan suburbs. So, strategies to maintain regional mobility in metropolitan suburbs are required.

Public transportation systems in metropolitan areas are generally large and require high service levels. So, it is unrealistic for municipalities to bear substantial operating costs. Even if there is some public burden, it is necessary to a strategy to maintain good mobility while maintaining a self-financing system in which users bear the operating costs. In a self-financing public transportation system, network structure and fare structure are closely related, and it is essential to optimize both elements simultaneously.

Network design problems have been studied mainly in traffic engineering, and fare design problems have been studied mainly in public economics. There are a few studies on the simultaneous optimization of network structure and fares, and there is no framework for analyzing the relationship between the optimal network structure and fares without limiting a specific network structure (e.g., grid, hub-and-spoke type) or fares to a uniform fare system or distance system.

This study focuses on systems consisting of buses in suburbs of large cities to show the need for simultaneous optimization of network structure and fares. I developed an optimization model as a framework for simultaneously determining optimal network structure, traffic volume, and fares to maximize social surplus under balance-of-revenue constraints, being able to consider various network structures and fares that can be price differentiated by OD. Through a theoretical analysis of the model, the basic properties of the optimal fares are clarified. Also, I took numerical analysis under several assumptions. I analyzed the specific relationships and properties of the optimum network structure, traffic volumes, and fares obtained through simultaneous optimization and confirmed the usefulness of simultaneous optimization.

Chapter 3 shows that the model to simultaneously determine a network structure, traffic volumes, and fares can be formulated as a mixed integer non-linear programming problem. In Chapter 4, it is shown that this model can be transformed into a two-level model consisting of an upper problem determining the network structure and a lower problem determining traffic volume

and fares, and a theoretical analysis of the lower problem consisting of continuous variables only is conducted. The results showed that the Ramsey price is adopted as the generalized payment, with some exceptions. Under the Ramsey rule, it is shown that a fare consists of an allocation of marginal operating costs and an additional allocation for each OD.

The allocation of marginal operating costs is larger for ODs using capacity-filled links. On the other hand, the additional allocation for each OD is affected by the marginal generalized cost, and its behavior depends on the functional form of the demand function via price elasticity. These features indicate that the optimal fare significantly depends on the shape of the demand function, the network shape, and the supply side's cost structure. On the other hand, the network structure is strongly influenced by fare revenues through income and balance-of-revenue constraints. So, it indicates that simultaneous optimization of the network structure, transport volumes, and freight rates is necessary.

In Chapter 3, it is shown that by assumptions of linearity of the demand function, the model can be attributed to a convex problem, the mixed integer quadratic cone programming problem, and it can be calculated numerically as a globally optimal solution. In Chapters 5 to 8, the optimal network structure, traffic, and fares are analyzed numerically for each specific case using the model.

Chapter 5 analyzes the optimum mode configuration under a fixed network using a simplified model version. Also, I analyzed the effect of reducing transfer resistance on the optimum mode configuration and total social surplus. The direct effect of reducing transfer resistance on total social surplus is insignificant, but modifying the mode configuration increases total social surplus. This suggests that flexible modification of the mode configuration is essential.

Chapter 6 presents a numerical analysis of the model under the condition that the network can be freely modified. ODs with higher journey times and higher transfer resistance have smaller fares. Optimal fares for ODs with capacity-fulled links are larger due to increasing the allocation of marginal operating costs. Therefore, if the marginal generalized cost can be reduced by bypassing a link with capacity-fulled capacity, even though the travel time is longer, the link with total capacity will be bypassed. In this case, the higher fares paid by users via the capacity-fulled link may clear most of the operating costs for the entire region, in which case fares on other ODs will be set very low.

Chapter 7 analyses the impact of making the fare system conform to the uniformity or the distance on efficiency and equity and the preferred fare system within the existing fare system. From an efficiency perspective, it is suggested that any fare system could produce a total social surplus similar to the optimal fare systems, except in cases where the fare level is too low to maintain an adequate network. On the other hand, from a fairness perspective, compliance with the current fare system could lead to significant differences in consumer surplus by residential nodes. A uniform fare system is desirable within the scope of the current fare system.

Chapter 8 analyses the impact of integrating the accounting of personal type vehicles and buses on network shape and consumer surplus by origin. It was shown that, in the case of integrated accounting, the introduction of buses increases the consumer surplus in the region, as personal-type vehicles transfer part of their fare revenue to the bus. Furthermore, if the bus passes through all nodes in the region and demand for the station is superior to other OD demands, accounting integration of personal type vehicles is expected to equalize consumer surplus by origin.

The numerical analysis results in Chapters 5 to 8 all show that network structure and fare setting are closely related, suggesting the importance of simultaneous optimization of network structure, traffic, and fares.

The specific characteristics of the optimal network structure, traffic, and fares depend on the demand and cost structures. The characteristics presented in the numerical analysis in Chapters 5 to 8 are some of the specific examples. Therefore, it is desirable to continue analyses under various assumptions to expand and refine the findings. However, the simultaneous network structure, traffic, and fare determination model presented in this thesis is an NP-hard problem, so its application to a large-scale network is challenging. In the numerical analysis in this paper, a linear demand function was assumed for numerical solvability. However, if a different demand function is assumed, the problem may not be convex, and an optimal solution may not be obtained. Developing solution methods and algorithms is necessary to overcome the above problems. Furthermore, extensions of the model and theoretical analysis focusing on the network structure are future tasks.