論文の内容の要旨

Dynamics of congested urban rail transit: a macroscopic model with demand and supply interaction

(需要供給統合化マクロモデルを用いた都市鉄道の混雑ダナミクス解析)

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Urban rail transit, with its high capacity and punctuality, serves as the major solution to commuters' travel demand during rush hours in most metropolises. However, travel experience of commuting by rail transit is frequently deteriorated by severe congestion and chronic delays. Moreover, passenger crowding both in-vehicle and on-platform and delays of trains can easily develop into a vicious circle especially in a high-frequency operated rail transit system. Therefore, a new solution to improve the level of service of congested rail transit is urgently needed.

On one hand, most of the efforts so far have been made to increase the supply of system, but these efforts are gradually reaching the ceiling due to financial and constructional limitations. On the other hand, practices of demand management for rail transit are still few and not successful to alleviate the congestion and delay issues. Most existing studies on rail transit optimization and management either treated passenger demand distribution as given information or ignored the influence of passenger demand concentration on railway operation. In order to derive insights into policy implications of management strategies, an appropriate model considering the interaction between demand and supply is indispensable for a congested rail transit.

The objectives of this study is threefold. First, to comprehensively understand influence of passenger demand concentration on rail transit operation by investigating a train fundamental diagram model and its variants using empirical data. Second, to macroscopically develop a dynamic model capable of describing equilibrium distribution of passenger arrivals in a congested rail transit system based on information of timetable and passenger preferences. Third, to derive insights into the design of probable management strategies and their combinations from a macroscopic view by applying the proposed model.

Through the analysis of Boston subway red line passenger flow and operation data, the influence of passenger demand concentration on rail transit operation is confirmed to be significant. By calibrating and evaluating the three variants (i.e., assumption of train dwell time constant, monotonically increasing or first constant then monotonically increasing with boarding passenger number) of rail transit fundamental diagram (train-FD) models using empirical data, the original train-FD model assuming monotonically increasing relation between trains' dwell time and waiting passenger number is found to be adequate to describe influence of passenger demand concentration from a macroscopic point of view.

The equilibrium model to describe passenger arrivals in a congested rail transit system is developed by employing the train-FD model with a novel particle-based dynamic approach. The conceptual structure of the proposed equilibrium model is a two-level model different from the existing one-level one for road traffic. The particle-based approach is found to be tractable for deriving insights into management strategies. A microscopic simulation program is also developed to verify the results from the equilibrium model. Outputs from the simulation and the model are found to be consistent to a great extent.

By applying the proposed model, three issues are investigated. First, optimum peak/off-peak timetable which minimizes the sum of travel time cost (TTC) and schedule delay cost (SDC) is explored. An optimum peak/off-peak timetable in free-flow regime of train-FD is proposed and numerically compared with different timetable patterns. Second, the user equilibrium under first-best pricing scheme is theoretically derived and numerically compared with the user equilibrium without pricing. Third, because the first-best pricing scheme requires time varying pricing which is difficult to realize in real world, an appropriate single-step coarse pricing scheme is specified and its effectiveness is numerically evaluated. The coarse pricing scheme is compared by indicators such as the change of sum of TTC and SDC, and change of in-vehicle crowding.

If all dispatched trains operate in free-flow regime of train-FD, peak/off-peak timetable is found to be optimized when average train flow before and after desired departure time are the same, and the flow of train with maximum passenger concentration reaches the critical state of train-FD. It is proved that the user equilibrium under first-best pricing scheme can significantly reduce the sum of TTC and SDC by flattening the change rate of riding passenger number among dispatched trains compared with the user equilibrium without pricing. Riding passenger number difference between successive trains under first-best pricing is exactly half of that in the equilibrium without pricing. The effectiveness of single-step coarse pricing is found to strongly depends on the temporal design of the scheme. The appropriately designed coarse pricing scheme without breaking the equilibrium shows an acceptable reduction of sum of TTC and SDC compared to the first-best one. Finally, a complex pricing scheme by jointly giving reward and imposing surcharge is examined, and it is found that a Pareto-improvement situation may occur depending on the timetable pattern with significant reduction of sum of TTC and SDC.