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Critical capacity, travel time delays and travel time distribution of rapid mass transit systems

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HIGHLIGHTS

- The travel statistics of the rail transport system (RTS) in Singapore is analyzed.
- Agent-based model is created that reconstruct the actual travel time of commuters.
- The validated model is used to investigate overloading and overcrowding dynamics.
- Existence of critical capacity resulting to exponential growth of delay is reported.
- The impact of various passenger growth distribution across stations is analyzed.

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ABSTRACT

We set up a mechanistic agent-based model of a rapid mass transit system. Using empirical data from Singapore's unidentifiable smart fare card, we validate our model by reconstructing actual travel demand and duration of travel statistics. We subsequently use this model to investigate two phenomena that are known to significantly affect the dynamics within the RTS: (1) overloading in trains and (2) overcrowding in the RTS platform. We demonstrate that by varying the loading capacity of trains, a tipping point emerges at which an exponential increase in the duration of travel time delays is observed. We also probe the impact on the rail system dynamics of three types of passenger growth distribution across stations: (i) Dirac delta, (ii) uniform and (iii) geometric, which is reminiscent of the effect of land use on transport. Under the assumption of a fixed loading capacity, we demonstrate the dependence of a given origin–destination (OD) pair on the flow volume of commuters in station platforms.

1. Introduction

Rapid mass transit systems (RTS) are becoming the foremost public transportation mode worldwide and recent literature indicates that as a city gets bigger and more urbanized, the more likely it is to develop a RTS [1]. Aside from the fact that RTS's significantly reduce traffic congestions, they offer a high frequency of service, catering to a greater volume of public commuters at higher velocities. Furthermore, mass transits put forward a significant decrease in the total carbon footprint and airborne pollution in cities compared to automobiles, and are considered to be the most energy efficient compared to

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other modes of transit [2,3]. In Singapore, for example, its RTS accounts for more than two million journeys per day across its 121 stations that are envisioned to continue on growing [4].

The social benefits of having a systematic RTS can be huge as it allows for the growth of employment opportunities, especially for citizens who are transit dependent; in addition, it provides access advantage to areas where boarding and alighting platforms are present, which further allows transit-related economic growth to thrive [5]. It cannot be overemphasized that ensuring the resilience and reliability of mass transit systems is critical in a bustling city. Potential damages and disruptions in the operations of these RTS do not only have a direct negative effect on its commuters such as delayed travel time; worse, they can generate unnecessary economic costs that can potentially harm local economies through cascades of failures.

Investigating various RTS scenarios is a non-trivial endeavor as it involves not just the understanding of the physical structure, but also of the behavior and interactions of its users, which give rise to emergent phenomena. In recent years, transportation professionals and researchers have explored the use of agent-based simulations (ABM) to tackle this complexity as it allows for provision of a "natural" description of a system [6–11]. This is especially useful in dealing with systems involving interacting behavioral entities. The use of ABM in transportation and traffic flow research is not new. It has been implemented to quantitatively assess impact of transport-related policies and other infrastructure changes [8,9]. However, transport-related ABM research has yet to reach its full maturity. Aside from the difficulty in assessing the outcomes of the simulations, there is also another challenge that mainly originates from the very nature of variables, which are thought to be "soft", and the intricacies involved in measuring the parameters [10–12].

In this paper, we hope to address the issue by setting up an empirically-driven, mechanistic-based ABM of the RTS. The ever increasing availability of large datasets has provided us with this opportunity to further advance the field by giving the simulations a more realistic flavor, among other things.

Here, we used key statistical features of the Singapore RTS such as the inter-arrival times of commuters in stations and the duration of travel time distribution of commuters for any given origin–destination (OD) pair to set up the simulations. We then validate the results by comparing with the actual recorded duration of travel time of commuters using a week's worth of smart fare card data. With an empirically verifiable model, we then explore population-related phenomenological scenarios deemed significant to the city and its planners such as the effects of train loading capacity and crowdedness of station platforms within the Singapore RTS.

2. Data

The dataset utilized was generated using Singapore's contactless smart fare ticketing card that automatically collects fares for its rapid transit system (RTS) and bus system. This was provided by the Singapore Land Transport Authority (LTA). Supposing that an individual takes an average of two rides per day (Home–Work/School–Home), the RTS is estimated to cater to around 20% of the country's ~5.3 million population daily. Other modes of transport include taxi, buses, walking and private cars. The data used include the following information:

- Anonymized card id
- Journey id
- Date of journey
- Origin station
- Destination station
- Tap-in time
- Tap-out time
- Distance travelled

The dataset contains information on 14 million journeys involving the usage of the RTS across a week's worth of service.

3. Agent-based model of RTS dynamics

We define our agent-based model (ABM) using three types of tractable agents as follows: commuter, train, and station. A schematic diagram of the RTS is shown in Fig. 1, where the unit of distance is represented by one track patch. Moreover, the system is constructed in a manner to reflect actual inter-station distances in the RTS.

The study focuses on a single full-length train track involving $S = 29$ actual stations within a Singapore RTS line (Fig. 1). The station numbers indicate station i.d.'s arranged in a sequential manner. The ABM deploys a total of D trains that would cater to all commuters within a day's worth of RTS service. The attributes associated with a train agent include time of dispatch, velocity, total capacity, current loading, and consequently, available capacity. Here, the velocity of the train is set to a value that is consistent with the actual distance and estimated journey time between any two consecutive stations within the RTS. Consistent with actual train dynamics, we employed two distinct train time dispatch intervals for peak (730–930 and 1730–1930 h) and off-peak hours, spread as a standard Gaussian distribution given by:

$$f(\tau) = \frac{1}{\sigma\sqrt{(2\pi)}} \exp\left(-\frac{(\tau-\mu)^2}{2\sigma^2}\right), \tag{1}$$