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Fundamental diagrams of airport surface traffic: Models and applications

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ABSTRACT

This paper reveals and explores the flow characteristics of airport surface network on both mesoscopic and macroscopic levels. We propose an efficient modeling approach based on the cell transmission model for simulating the spatio-temporal evolution of flow and congestion on taxiway and apron networks. The existence of link-based fundamental diagram that expresses the functional relationship between link density and flow is demonstrated using empirical data collected in Guangzhou Baiyun airport. The proposed CTM-based network model is shown to be an efficient and accurate method capable of supporting air traffic prediction and decision support. In addition, using both CTM-based simulation and empirical data, we further reveal the existence of an aggregate relationship between traffic density and runway throughput, which is referred to as *macroscopic fundamental diagram* (MFD) in the literature of road traffic. The MFD on the airport surface is analyzed in depth, and utilized to devise several robust off-block control strategies under uncertainties, which are shown to significantly outperform existing off-block control methods.

1. Introduction

Air traffic flow management seeks to balance air traffic demand and supply in such a way that improves air traffic efficiency and reduces flight delays. As the most stringent bottleneck in the air traffic network, airport surface (including apron areas, taxiways and runways) is often subject to severe traffic congestion, such as stop-and-go movements, excessive runway queuing, and even gridlock, which leads to the increase of taxi time, fuel burn and emission. Severe congestion facing departure traffic at airport surface has now become a major challenge in air traffic management (Balakrishnan and Jung, 2007).

Earlier work on the congestion mitigation for departure traffic on airport surface has primarily focused on the optimization of taxiway operation, which is typically formulated as mixed integer linear programs (Marín and Codina, 2008), or solved with metaheuristic methods (García et al., 2005). Taxiing optimization problems seek to assign to each aircraft taxiing route and *required time of arrival* (RTA) at the key nodes along the route to avoid conflicts and improve taxiing efficiency (Yang, 2012). In 2009, EUROCONTROL proposed the operational concept of DMAN (Departure Manager), and that “maintaining the optimal number of aircraft on the taxiway” is a key undertaking of DMAN (Burgain, 2010).

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The key to the understanding and mitigation of airport surface congestion is to capture, in an effective way, traffic flow characteristics and mechanisms under which congestion forms, propagates, and dissipates. Traditional methods in this regard include statistical methods (Shumsky, 1995; Idris et al., 2010), stochastic queuing models (Pujet et al., 1999; Simaiakis and Balakrishnan, 2009), and microsimulation methods (Couluris et al., 2008; Nakamura et al., 2010; Ryota, 2013). However, statistical methods and queuing network models do not capture the flow characteristics of traffic in the surface network (such as acceleration, deceleration, merging and diverging behavior) or congestion caused by factors other than runway queuing (such as delay at network nodes due to conflict). Although microsimulation models, if well calibrated, could accurately describe the network traffic dynamics, they typically require substantial computational time and do not provide timely and robust outcome for real-time application.

Given the similarities between airport surface traffic and network car traffic, and inspired by the mesoscopic traffic modeling (Daganzo, 1994; 1995), this paper proposes an adaptation of the *cell transmission model* (CTM) to describe and predict the dynamics of flow and congestion on airport surface networks. Mesoscopic traffic models ignore certain granularities at the individual level, and capture the aggregate dynamics in a robust and computationally efficient way. In particular, we describe the flow propagation within links using the *fundamental diagram* (FD), which expresses the relationship between link flow and density. Junction movements such as merge, diverge, and crossover are modeled using the notions of demand and supply that interact under specific protocols. Moreover, modeling scenarios unique to airport surface, such as runway queuing and apron traffic, are integrated into the CTM framework. Overall, the proposed mesoscopic modeling framework is flexible in accommodating different network topology and flow characteristics, and computationally tractable to support strategic planning and real-time operation.

To the best of the authors' knowledge, this study is the first to explore the link-based FD on airport surface for the modeling and simulation of surface traffic. The FD is calibrated and validated using empirical data from Guangzhou Baiyun Airport (ZGGG) in China. As an immediate application, we use the CTM to derive a network-level *macroscopic fundamental diagram* (MFD), which is again validated using empirical data. The MFD (Daganzo, 2007) characterizes the aggregate behavior of the network traffic in terms of average density and trip completion rate, in a parsimonious way capable of capturing the key demand-supply interactions. The MFD aims at reducing the modeling complexity while capturing the main dynamic features of congestion. The main concept is to utilize the MFD models to manage large-scale networks in hierarchical control approach, having the capability of integrating the collective behavior of the network in the local control decisions. The MFD is the basis for a variety of flow control algorithms aiming at maximizing the network performance of a particular transportation system, see Section 2.2.

The same concept of the MFD can be applied for airport surface traffic. In a recent study (Simaiakis et al., 2014), an aggregate curve, which relates the jet take-off rate as a function of the number of departing aircraft on the ground, is utilized to devise a simple yet effective off-block control. However, that method embraces a simplistic bang-bang control strategy, with idealized curve parameterized by the number of arrivals and absence of uncertainties. In this paper, we first demonstrate the existence of an MFD curve for airport surface, and then we propose a robust off-block feedback control that incorporates a range of uncertainties in the MFD, arrival rate, and taxi-out traffic. Different variants of the robust control are compared with the one from Simaiakis et al. (2014) using the CTM-based simulation platform for the case study of ZGGG, and are shown to yield superior performance in terms of reducing total delay and runway queuing.

The main contribution of this paper may be summarized as follows:

- We propose a mesoscopic dynamic model for airport surface networks based on the CTM. The existence and validity of the FD is shown with empirical data, so is the accuracy of the proposed model in capturing network-wide propagation of flow and congestion.
- Using the CTM-based simulation platform, we derive a network-level MFD for the Guangzhou Baiyun Airport, which is verified against an empirical MFD for the same network. This further proves the consistency of the propose mesoscopic model with aggregated dynamics on a network level.
- Several new robust off-block control strategies are proposed based on the MFD, which outperform existing ones (Simaiakis et al., 2014) in terms of reducing departure delays and runway queuing in a variety of uncertain environments. This is demonstrated on the CTM-based simulation platform.

The CTM-based mesoscopic network model is sufficiently general to support a wide range of tasks involved in the design, planning, and operation of airport surface traffic. It captures realistic taxiing traffic dynamics such as free-flow, trailing, turning maneuver, queuing, and holding, with intuitive parameters and rules. Its computational efficiency over microsimulation, as adequately shown for vehicular traffic, makes it an attractive modeling platform for airport traffic research. These have been shown in this paper through the discovery of a MFD for the airport surface traffic and the evaluation of a number of off-block control strategies.

The rest of this paper is organized as follows. Section 2 provides a review of relevant literature on departure traffic modeling and macroscopic fundamental diagram. In Section 3 we present the cell transmission model and its adaptation to airport surface network. Section 4 reveals the MFD on airport surface based on empirical data, and devise several MFD-based robust off-block control methods to mitigating surface congestion on airports. We show the details of the CTM on airport surface and validate its modeling accuracy using empirical data in Section 5. Section 6 presents a case study of the off-block controls on a real-world airport operational environment. Finally, Section 7 provides some concluding remarks.