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Modeling flight delay propagation: A new analytical-econometric approach

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ABSTRACT

Flight delay presents a widespread phenomenon in the air transportation system, costing billions of dollars every year. Some delay originating from an upstream flight spreads to downstream flights. This phenomenon is defined as delay propagation. To understand the delay propagation patterns and associated mitigation measures, this study proposes a novel analytical-econometric approach. Considering that airlines deliberately insert buffer into flight schedules and ground turnaround operations, an analytical model is developed to quantify propagated and newly formed delays that occur to each sequence of flights that an aircraft flies in a day, from three perspectives on the ways that delays are absorbed by the buffer. With delays computed from the analytical model, we further develop a joint discrete-continuous econometric model and use the Heckman's two-step procedure to reveal the effects of various influencing factors on the initiation and progression of propagated delays. Results from the econometric analysis provide estimates on how much propagated delay will be generated out of each minute of newly formed delay, for the US domestic aviation system as well as for individual major airports and airlines. The impacts of various factors on the initiation and progression of propagated delay are quantified. These results may help aviation system planners gain additional insights into flight delay propagation patterns and consequently prioritize resource allocation while improving system overall performance. Airlines can also be better informed to assign buffer to their flight schedules to mitigate delay propagation.

1. Introduction

Flight delay is a major challenge facing the air transportation system today. In the US, total flight delay cost is estimated to be over $30 billion each year (Ball et al., 2010). The cost comes from various sources, including additional use of crew, fuel, and aircraft maintenance; increase in passenger travel time; greater environmental externalities; and the macroeconomic impact of flight delay on other economic sectors. While solutions such as improvement in air traffic management (e.g., Ball et al., 2007; Swaroop et al., 2012) and aviation infrastructure investment (Zou and Hansen, 2012a; Zou, 2012) are expected to substantially reduce flight delays, an important means from the airlines' perspective is to judiciously schedule flights. Specifically, by inserting additional times than the minimum necessary in and between flights, unexpected delays can be absorbed and consequently their propagation to downstream flights can be mitigated or avoided. The objective of this study

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is to advance the understanding of the delay propagation patterns and of the ways delays are mitigated by the additional times.

Propagated delay occurs because of connected resources involved in an initially delayed flight and flights downstream. The connected resources can be the aircraft, crew, passengers and airport resources. For example, the same aircraft flies multiple flight legs in a day. Delay of an earlier flight can sustain in the subsequent flights of the same aircraft. Flight crew can also switch between multiple aircraft, causing the delay from one flight to propagate across multiple flights. Connecting passengers at hub airports, like crew members, are also often responsible for the propagation of delay when a connecting flight has to wait for passengers from their previous delayed legs. Overall, delay can grow over the course of a day, with a small initial delay leading to larger delays later in the day. To mitigate this propagation effect, additional times are inserted in both flight schedules and ground turnaround operations. In this study, we term these additional times as flight buffer and ground buffer. The buffer can be interpreted as the *ex-ante* amount of time built into a scheduled activity based on an expected amount of time for an activity plus an amount to maintain a level of on-time service. To some extent, it is analogous to an inventory problem.

In the literature, analytical research on flight delay propagation dates back to 1999, when Beatty et al. (1999) used flight schedules of American airlines to calculate delay propagation multipliers. A delay propagation multiplier is a value which when multiplied with the initial delay yields the sum of all potential downstream delays plus the initial delay. Beatty et al. constructed delay trees by considering three causes for delay propagation: aircraft equipment, cockpit crew, and flight attendants. A delay tree can contain up to 50–75 flights for a flight early in the day that is connected to the rest of the system. However, the authors did not show how delays can be absorbed by flight and ground buffers. AhmadBeygi et al. (2008) also constructed tree structure to investigate how delay can propagate throughout an airline's network in a day, for two US airlines. In the delay tree, the root delay, which occurs to the earliest flight in the tree, propagates to immediate downstream flights of the same aircraft. In cases that the cockpit crew and aircraft do not stay together, delay propagates to the flight the cockpit crew heads. Ground buffer was accounted for as a means to mitigate delay propagation. However, propagated delays due to connecting flight attendants or passengers and the delay recovery options were not included in the analysis. Welman et al. (2010) calculated delay multipliers for 51 US airports and estimated the reduction in total system delay if airport capacity was expanded. Buffer was not included while calculating propagated delay. Churchill et al. (2010) developed another analytical model, which explicitly accounts for ground buffers but not flight buffer. A measure for the level of network-wide extension of flight delays was introduced in Fleurquin et al. (2013) to define when an airport is congested and study how congested airports form connected clusters in the network.

Apart from the analytical approaches, other methods were used in flight delay propagation research. Wong and Tsai (2012) considered simultaneously flight and ground buffers and statistically estimated a survival model for flight delay propagation. Xu et al. (2008) used multivariate adaptive regression splines and found on average 5.3 min of generated delay and 2.1 min of absorbed delay across 34 Operational Evolution Plan (OEP) airports in the US. Pyrgiotis et al. (2013) developed a queuing engine to model flight delay formed at an airport. The formed delay was then utilized to modify the flight schedules and update demand at the airports. The two processes iterate to obtain the final local delay formed at an airport and its propagation. Most recently, Campanelli et al. (2016) used two agent-based models to simulate flight delay propagation and assessed the effect of disruptions in the US and European aviation networks.

While inserting buffer is an effective means to mitigate delay propagation, doing so has adverse effects. First, buffer makes flight schedules and ground turnaround times longer than the minimum necessary, reducing the utilization of aircraft and incurring greater capital cost. Second, because payment to airline crew is determined in part by the length of flight schedules, inserting flight buffer increases crew expenses. Third, with flight buffer, flights often arrive earlier when there is no delay. The landed aircraft are likely to encounter gate unavailability and thus have to wait in queue on the ramp with engines on, which increases airline operating cost and ramp congestion, and potentially aggravates passengers onboard (Hao and Hansen, 2014). These adverse effects prompt airlines to consider the best tradeoff when setting buffers in their flight schedules. Following this line of thought, AhmadBeygi et al. (2010) investigated the issue of reallocating ground buffer by re-timing flight departures, such that delay propagation can be mitigated without incurring additional planned cost. Monte Carlo simulations were performed in Schellenkens (2011) to establish the relationship between the duration of primary delays and the number of affected downstream flights. Focusing on delay propagation, Arikan et al. (2013) proposed several metrics to investigate the robustness of US airline schedules, and showed different airline strategies in setting flight and ground buffers.

Despite these efforts for modeling propagated flight delay, two important methodological gaps exist. First, no studies have so far looked into simultaneous use of flight and ground buffers in absorbing both propagated and newly formed delays. At a given flight arrival or departure point (or node, as we define in the next section), newly formed delay is defined as the delay that occurs during the immediate upstream operation (which can be either a flight or a ground turnaround); whereas propagated delay is delay that is rooted further upstream. Among the aforementioned studies, Churchill et al. (2010) and Arikan et al. (2013) considered only ground buffer. Although both flight and ground buffers were modeled in Schellenkens (2011), the authors did not differentiate between newly formed and propagated delays, nor the way the two types of delays are absorbed by buffer. In fact, there is no way to get specific empirical data on the two types of delays. Yet with the coexistence of propagated and newly formed delays, buffer could be used to first absorb newly formed delay and then propagated delay, or vice versa, or both at the same time. To fill this gap, the present study explicitly