EFFECTS OF AIRPORT MOVEMENTS ON TAXI-IN AND TAXI-OUT TIME

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ABSTRACT

Aircraft movements resulting from landing, take-off, and taxi operations are a determining factor for airport capacity. To enhance ground traffic management efficiency and gain a more precise understanding of factors influencing taxi times, it is imperative to obtain more accurate taxi time predictions. However, Exploring the extent to which aircraft arrivals and departures at an airport can disrupt taxi times and lead to practical consequences remains little explored. This paper utilizes real data from prominent Brazilian airports with substantial traffic to assess the impact of airport movements on taxi times, both for taxi-in and taxi-out. A regression analysis has been applied to evaluate significant variations across ten Brazilian airports during the peak months of July, August, and December 2022, when aircraft movements were at their highest. The results demonstrate alterations in taxi times at the airports under examination. For instance, at Porto Alegre Airport, each departing aircraft extends the ground taxi time by 1.10 minutes for other moving aircraft. Similarly, at Salvador Airport, each arriving aircraft can increase the taxi time for a taxiing aircraft by 0.25 minutes. In the case of taxi-out operations, every arriving aircraft increases the taxi time by 0.57 minutes at São Paulo - Congonhas Airport and at São Paulo - Guarulhos Airport, every departing aircraft increases the taxi time for another taxing aircraft by 0.32 minutes. Therefore, addressing the impact of air movement at airport can provide valuable insights and facilitate the development of strategies aimed at mitigating taxi times.

Keywords: Aeronautics infrastructure, Air transport, Operational efficiency

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2. INTRODUCTION

Taxi time management is one of the main indicators to assess the operational efficiency of an airport, so that additional surface movement times can generate a bottleneck in air operations. In airports where air traffic reaches or nearly reaches maximum airport capacity, it can cause delays and long taxi times, as well as reduce the availability of circulating aircraft (Li et al, 2020).

It is estimated that 10-30% of total flight time is spent while taxiing in Europe (Simaiakis and Balakrishnan, 2009). The taxiing procedure applies along the path of an aircraft from the gate to the runway threshold or vice versa. However, many times this trajectory may exceed the expected taxi operating time due to several factors, such as severe meteorological events (Cheng et al., 2019; Zou et al., 2018), airport terrain uncertainties, airport layout, infrastructure, airport capacity (Park and Kim, 2023; Wang et al., 2021a) and other unpredictable factors.

The implementation of surface traffic management can improve air operations, avoiding undesirable problems such as congestion (Murça, 2017). In addition, the ability to predict phenomena that affect taxi times variability allows avoiding stop-and-go situations, reducing queues and minimizing the additional effort required from controllers to avoid waste and ensure operational safety, as mentioned by Nikoleris et al. (2011).

By analyzing the causes and seeking solutions to reduce additional taxi time, efforts are being made to improve the predictability and efficiency of air operations through the reduction of congestion on taxiways and optimization of travel times. Additionally, this approach aims to minimize environmental impacts, with the reduction of carbon emissions, thus making the aeronautical industry more efficient and responsible, according to the research by Postorino et al. (2019).

Understanding additional taxi time is the first step to optimize taxi time, reducing waiting times, decreasing fuel consumption, and enhancing predictability in airport operations. By comprehending the time wasted in ground traffic at an airfield enables the implementation of strategies to improve overall efficiency. This step aligns with the objective of this study, which is to investigate the variation of taxi-in and taxi-out time duration resulting from aircraft movement at airports. In this study, 10 Brazilian airports were selected to observe variations in taxi time.

3. THEORETICAL BASIS

Several existing studies on aircraft ground movement indicate that the main operational bottlenecks are primarily related to aeronautical infrastructure, including runway capacity, runway configurations and runway intersections (Park and Kim, 2023; Wang et al., 2021a, Ravizza et al., 2013). Various variables associated with taxi time for specific aircraft are discussed in the literature. These variables include weather factors (Park and Kim, 2023; Li et al, 2020), taxi distance (for taxi-in), instantaneous airport traffic flow (for taxi-out) (Jiao and Li, 2022; Li et al., 2020) and technical failures during flight departure, resulting in delays in arrival at the destination airport and therefore affecting airport capacity (Cheng et al., 2019).

Operations of landing, takeoff, and aircraft movement on the ground can restrict airport capacity and increase surface movement time. When using hierarchical regression to construct a predictive model of taxi time, Lordan et al. (2016) found that the expected taxi route to be traversed and factors influencing a quick departure (for landings), such as aircraft deceleration, and the runway (for takeoffs), including gate position and queues before takeoff, are directly related to taxi time. Using Cox regression, Diana (2013) demonstrates that gate departure delays and airport capacity availability impact taxi-out time in instrument meteorological conditions (IMC). In other words, there is approximately an 80% increase in taxi time for every 1% increase in airport capacity utilization.

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Ground movement is a determining factor for airport capacity. Zou et al (2018), using Monte Carlo simulation, predict the dynamics of aircraft movement on the ground in a real situation, using the concept of "Runway Exit Availability" (REA) and a two-stage scheduling strategy to deal with the problem of uncertain exits. The authors demonstrate an aggregate time saving of approximately 50% for departures and arrivals. However, they do not consider external factors that impact time, such as weather conditions and speed profiles in practice related to operational constraints.

Improving air operations management allows for efficiency gains in terms of time and minimization of environmental impacts, delays and unnecessary costs. With this objective, Simaiakis and Balakrishnan (2009) investigate the possibility of reducing fuel consumption and gas emissions in surface operations by reducing taxi time, through organizing aircraft in queues, as presented in Figure 1.

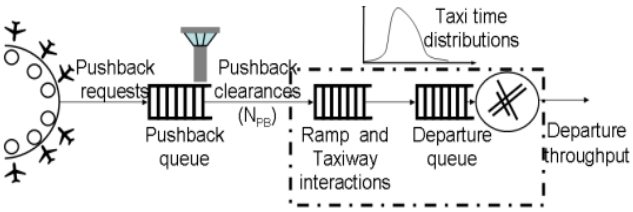


Figure 1: Controlled departure process. Source: Adapted from Simaiakis and Balakrishnan (2009).

According to Figure 1, the model proposed by Simaiakis and Balakrishnan (2009) uses gate-hold strategies to control congestion, with the aim of reducing taxi time. However, in this approach, the authors do not prioritize the pursuit of punctuality in operations, which is a relevant factor for airlines.

Regarding the motivations that cause inefficiencies in surface operations to achieve superior operational performance, Wang et al. (2021a) present the key-factors that affect taxi time in ground airport movements using a Random Forest prediction model. Using real data from three international airports (Manchester, Zurich, and Hong Kong) during the winter and spring months, the study reveals that the number of aircraft moving from pushback to the runway, the number of ground maneuvers, taxi distances over 500m, and the average speed of arriving and departing aircraft have an impact on taxi time.

In addition to these insights that affect aircraft taxi time prediction, Wang et al. (2021b) address the optimization of taxi time under uncertainty using the chance-constrained programming (CCP) model and propose a modified algorithm with a heuristic method that seeks the fastest route to simulate more efficient route allocation. The CCP model tested at Manchester Airport (MAN) in the UK proves to be efficient with fewer stops during the taxiing process, but it does not use real-time data in the simulations or address capacity bottlenecks during peak hours and heavy traffic.

There has been further research investigating the variation in taxi time. Ravizza et al. (2013) use a multiple linear regression approach to estimate factors that affect taxi time, revealing that taxi distance is related to aircraft speed, where arriving aircraft (taxi-in) have a higher speed compared to departing aircraft (taxi-out). Additionally, the turning angle was identified as a factor that contributes to reducing aircraft speed during taxiing. Aspects that cannot be easily explained, such as pilot behavior or airline standardization, also influence taxi time.

Predicting pushback time, taxi time, and runway utilization using deterministic optimization models proves to be a challenging task. Recognizing this limitation, Murça (2017) proposes a robust optimization approach that utilizes stochastic simulation of aircraft departure performance, taking into account the uncertainty of taxiing time. With this approach, it was possible to minimize surface congestion by establishing more

appropriate times for aircraft release from the gate in anticipation of potential surface delays.

Quantifying operational time presents challenges due to ongoing events in airport structures, such as truck traffic, de-icing processes, engine tests, and firefighting drills. These events generate variations in surface traffic time. As a result, the parameters adopted by the International Civil Aviation Organization (ICAO) to measure taxi time, fuel flow, and emission indices may be inconsistent and, in some situations, overestimated compared to actual operations. This discrepancy was observed by Xu et al. (2020), who modeled fuel consumption and emissions using real aircraft operational data at Shanghai Pudong International Airport during the taxi phase. It was found that taxi-out time is generally 35% longer, while taxi-in duration is closer to the operational time established by ICAO.

ICAO (2020) recommends that aeronautical operators measure taxi times for both taxi-in from the runway to the terminal and taxi-out from terminal to the runway. These measurements should consider wait times at the boarding gates, taxiway configurations, gate configurations and aircraft type.

An optimized approach that incorporates real airport data depicting how airport capacity affects taxi time is increasingly valued. There are various causal factors shown in the literature that interfere with taxi time, such as weather conditions, gate-to-takeoff delay, air traffic, airport congestion, and other factors that can result in increased taxi time. However, understanding how the movement of arriving and departing aircraft at an airport can interfere with taxi time and generate practical results remains little explored. This study aims to fill this gap.

4. METHODS

In this study, data collection and analysis were conducted regarding the taxi times of specific aircraft for takeoff (taxi-out) and after landing (taxi-in) at Guarulhos (SBGR), Congonhas (SBSP), Brasília (SBBR), Campinas (SBKP), Curitiba (SBCT), Porto Alegre (SBPA), Cuiabá (SBCY), Vitória (SBVT), Campo Grande (SBMS), and Salvador (SBSV) airports. The selection of these airports was motivated by their high airport movements in Brazil in 2022, with SBGR having 245,163 movements, SBSP with 197,184, SBBR with 135,626, SBKP with 128,564, SBSV with 76,365, SBPA with 66,140, SBCT with 56,058, SBCY with 44,975, SBVT with 40,128, and SBMS with 25,149 movements between landings and takeoffs. These airports have different taxiway and runway layouts, allowing for the analysis of the impact of runway configurations at different levels of interaction.

Data was collected from the dataset provided by the National Civil Aviation Agency (ANAC) on aircraft movements on the ground, both for domestic and international flights. By combining the data, it was possible to extract the demand at these airports. The data was restricted to the months of July, August, and December 2022, which recorded the highest number of commercial and general aircraft movements throughout the year. For the purposes of this study, the variation in taxi time was presented in Equation 1.

$$\Delta T\ 1 = |ATOT - AOBT| \quad (1)$$

being T1 the taxi-out time, the difference between the ATOT (Actual take-off time) and the AOBT (Actual off-block time), which is the difference between the departure time and the "off-block" time. According to Simaiakis and Balakrishnan (2009), the taxi-out time of an aircraft consists of three elements: unimpeded taxi time, waiting time in the departure queue, and delay caused by congestion resulting from interactions between the ramp and the taxiway.

$$\Delta T\ 2 = |AIBT - ALDT| \quad (2)$$

being T2 the taxi-in time, the difference between the AIBT (Actual in-block time) and the ALDT (Actual landing time), which is the difference between the "in-block" time and the landing time.

Based on the data analysis, data from general aviation were omitted in order to classify commercial aviation into aircraft of the

same size (Lieder et al., 2014, Ravizza et al., 2014) with similar sizes, shapes, weight, and parking positions.

Finally, a regression analysis was performed to test statistically significant differences among the perspectives presented by each airport in the months of July, August, and December (2022), which are the periods with the highest aircraft movements in 2022. The statistical modeling is presented by Equation 3.

$$Yi = \alpha + \beta iXi + ... + \beta pXp + \varepsilon i \quad (3)$$

where Y is the actual observation of the taxi-in or taxi-out time; α represents the intercept of the regression line (constant); βiXi + ... + βpXp refers to the independent variables of the model; and εi represents the random error associated with each observation.

5. RESULTS ANALYSIS

Upon closer examination of airport operations, it is evident that an aircraft in the process of taking off or landing can have an impact on the taxi time of another aircraft on the ground. The novelty of this study is to quantify how much a single aircraft affects the taxi time of another aircraft.

In the process of measuring the variation in taxi time due to aircraft movements at airports, the number of aircraft transitioning from the gate to the ends of the runway was taken into account, as well as the number of arriving (after landing) and departing (before takeoff) aircraft. This approach allowed for determining the variation in taxi-in and taxi-out times.

Taxi-out time

A separate regression was performed for each airport. Thus, it is possible to observe the constant (intercept) for each airport, which represents the estimated value of the dependent variable when all independent variables are equal to zero. It was found that Congonhas (SBSP), Brasília (SBBR), Campinas (SBKP), and Salvador (SBSV) airports experienced impacts on taxi-out time due to arriving and departing aircraft. On the other hand, Guarulhos (SBGR), Curitiba (SCCT), Porto Alegre (SBPA), and Vitória (SBVT) airports had their taxi time altered solely due to departing aircraft.

Table 1: Departures and arrivals for taxi-out

AIRPORT	PROCEDURE	ESTIMATE	STD ERROR
(Intercept)		11.98	0.16
SBBR	departure	0.35	0.01
	arrival	0.14	0.04
(Intercept)		6.96	2.01
SBSP	departure	1.09	0.03
	arrival	0.14	0.07
(Intercept)		6.08	0.62
SBSV	departure	0.93	0.03
	arrival	0.25	0.08
(Intercept)		8.64	0.66
SBCT	departure	0.93	0.07
(Intercept)		12.90	0.22
SBGR	departure	0.88	0.01
(Intercept)		5.46	0.36
SBPA	departure	1.10	0.05

Multiple R^2: 0.4686 Adjusted R^2: 0.4672

All p-value is < 0.05

Source: research data.

According to Table 1, for every departing aircraft from Brasília Airport (SBBR), the taxi time for an aircraft taxiing from the gate to the runway increased by 0.35 minutes. And for every arriving aircraft from the same airport, the taxi-out time for an aircraft increased by 0.14 minutes. The same trend can be observed for the other airports in Table 1.

The main objective of demonstrating the variation in taxi time from one airport to another is to test whether there is a consistent trend among airports or if taxi time varies

according to the configuration and layout of each airport, as pointed out by Ravizza (2013). The average taxi-out time for every departing aircraft is 3.6 minutes at Guarulhos Airport (SBGR) and 0.11 minutes at Vitória Airport (SBVT). While for every arriving aircraft, the average taxi-out time is 0.2 minutes at Campinas Airport (SBKP) and 0.08 minutes at Congonhas Airport (SBSP), as shown in Figure 2.

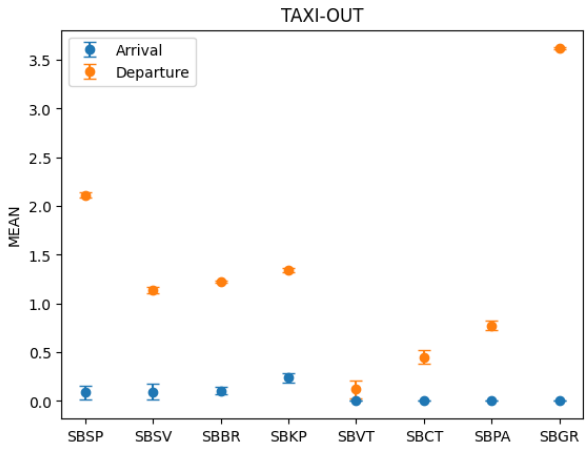


Figure 2: Average taxi-out results.
Source: the authors

When surface traffic operations occur near maximum capacity, congestion can arise both on taxiways and in holding areas. This situation leads to delays in aircraft movement, which in turn can increase taxi-out time (Diana, 2013; Simaiakis and Balakrishnan, 2009; Wang et al., 2021).

Taxi-in time

A separate regression was also performed for taxi-in for each airport, resulting in separate constants. From the analysis, it was noted that the airports of Brasília (SBBR), Guarulhos (SBGR), Campinas (SBKP), and Salvador (SBSV) experienced impacts on the time for both arriving and departing aircraft. On the other hand, the airports of Curitiba (SCCT), Cuiabá (SBCY), Porto Alegre (SBPA), and Congonhas (SBSP) had their taxi-in time altered only due to arriving aircraft.

Table 2: Departures and arrivals for taxi-in

AIRPORT	PROCEDURE	ESTIMATE	STD ERROR
(Intercept)		8.20	0.09
SBBR	departure	0.16	0.01
	arrival	0.12	0.02
(Intercept)		6.29	0.25
SBGR	departure	0.32	0.01
	arrival	0.36	0.02
(Intercept)		7.15	1.22
SBKP	departure	0.15	0.02
	arrival	0.28	0.03
(Intercept)		2.83	0.35
SBSV	departure	0.19	0.03
	arrival	0.11	0.04
(Intercept)		4.36	0.33
SBCT	arrival	0.21	0.07
(Intercept)		4.35	0.19
SBCY	arrival	0.23	0.13
(Intercept)		4.47	0.26
SBPA	arrival	0.48	0.07
(Intercept)		5.77	1.19
SBSP	arrival	0.57	0.03

Multiple R^2: 0.4182 Adjusted R^2: 0.4167
All p-value is < 0.05
Source: research data.

According to Table 2, for each aircraft departing from Brasília Airport (SBBR), there was an increase of 0.16 minutes for an aircraft taxiing from the gate to the runway threshold. And for each aircraft arriving from the same airport, there was an increase of 0.12 minutes for an aircraft performing taxi-out. The same trend can be observed for the other airports in Table 2.

As seen in Figure 3, the average taxi-in time is very low, with 0.86 minutes at Guarulhos Airport (SBGR) and 0.12 minutes at Salvador Airport (SBSV) for each departing aircraft. As for arriving aircraft, the average taxi-in time is almost irrelevant, with Guarulhos Airport (SBGR) having the highest average of 0.6 minutes.

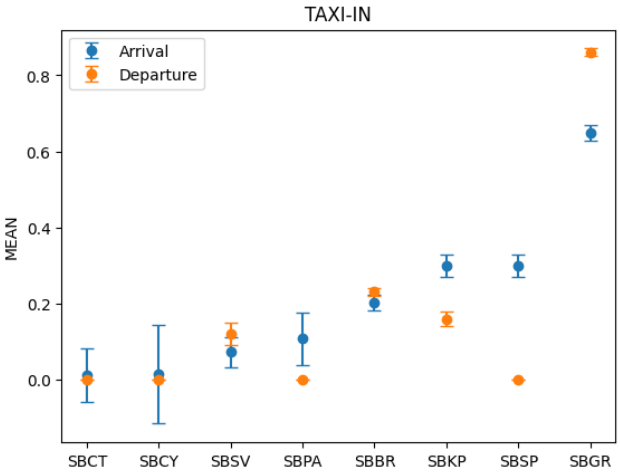


Figure 3: Average taxi-in results.
Source: the authors

The time required to travel each segment of the taxiways is constant. However, as indicated by Xu et al. (2020) and Diana (2013), the taxi-out time is greater than the taxi-in time, probably motivated by the increase in capacity caused by queuing aircraft about to take off, as arriving aircraft tend to quickly vacate the runway through REA and reach the gate (Zu et al., 2018; Lordan et al., 2016). Furthermore, aspects related to the runway layout contribute to the variation in taxi time (Wang et al., 2021b), as evidenced by our model when the largest airport in the model, Guarulhos Airport (SBGR), showed a higher variation in taxi time.

According to the analysis, taxi time is affected by the number of arriving and departing aircraft and the number of aircraft in transit on the movement area. This aircraft traffic and the runway configuration, due to travel distance, influence delays and runway congestion. As shown in Table 1 and Table 2, using only aircraft movements explains part of the variation in taxi time, with an R^2 value of 0.46 for taxi-out and 0.41 for taxi-in. In contrast, the R^2 presented in the model by Park and Kim (2023) indicated an R^2 of 0.27 for taxi-in and 0.70 for taxi-out. Similarly, in the model presented by Wang et al. (2021a), the R^2 ranges from 0.56 to 0.81 when introducing weather conditions as a determining factor for time variation.

The variation in taxi time shown in this study with 10 Brazilian airports enables better management of surface traffic. Therefore, the results of this research can be applied to improve the prediction of total taxi time for an airport, as well as assist planners and decision-makers in developing alternatives aimed at meeting demand, defining market strategies, and avoiding time and financial wastage resulting from operational bottlenecks at airports.

6. CONCLUSIONS

Taxi time directly affects the takeoff and landing sequence on the runway, which consequently impacts the operational efficiency of the airport. In this article, we aimed to analyze the variation in taxi time based on airport movements using a data-driven approach.

The inclusion of 10 Brazilian airports was beneficial for the purpose of comparisons and to understand how arrivals and departures of aircraft affect each airport. Certainly, there are opportunities for improving the accuracy of the models regarding the results and incorporating other factors that affect taxi time, such as weather conditions and subjective factors like airline standardization, which would provide insights to achieve this objective. Consequently, it would likely increase the explanatory power of the model as indicated by R^2. The model's explanatory capacity can also be enhanced by employing robust methods such as machine learning or other regression approaches.

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