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# Estimation of aircraft taxi fuel burn using flight data recorder archives

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ABSTRACT

This paper builds a model for estimating the fuel consumption of a taxiing aircraft using flight data recorder information from operational aircraft. The taxi fuel burn is modeled as a linear function of several potential explanatory variables including the taxi time, number of stops, number of turns and number of acceleration events, and the coefficients are estimated using least-squares regression. The statistical significance of each potential factor is investigated. Our analysis shows that in addition to the taxi time, the number of acceleration events is a significant factor in determining taxi fuel consumption. Since the model parameters are estimated using data from operational aircraft, they provide more accurate estimates of fuel burn than methods that use idealized physical models of fuel consumption based on aircraft velocity profiles, or the baseline fuel consumption estimates provided by the International Civil Aviation Organization.



## 1. Introduction

Estimation of aircraft fuel burn plays an important role in calculating the environmental impact of air traffic operations as well as in estimating the benefits of congestion control methods, and has been a topic of interest to the research community for several years (Collins, 1982). Taxi fuel consumption is most often determined using the fuel burn indices listed in the International Civil Aviation Organization (ICAO) engine emissions databank (International Civil Aviation Organization, 2008). The fuel burn indices provide fuel burn rates for only four engine power settings (corresponding to 7% or taxi/idle, 30% or approach, 85% or climb-out, and 100% or takeoff), and are based on estimates provided by engine manufacturers (Intergovernmental Panel on Climate Change, 1999; Kim and Rachami, 2008).[1]

In contrast, to estimate the benefits of surface traffic management strategies, it is necessary to have separate estimates of the taxi (on-surface) fuel burn. Previous studies on this topic (Jung, 2010) have used the ICAO fuel burn indices (augmented by physical models) for this purpose. These indices are obtained by engine manufacturers from staged tests of new, uninstalled engines, and therefore may not be representative of operational aircraft. Alternatively, studies have assumed different taxiing modes (ground idle at 4% thrust, taxi at constant speed at 5%, breakaway at 9%, and perpendicular turns at 7%) and used linear interpolation of the ICAO fuel indices between 7% and 30% thrust (Nikoleris et al., 2011). However, these assumptions about the thrust settings as well as the linear interpolation of fuel burn indices have not been validated with data. To the best of our knowledge, this paper presents the first attempt to develop models of aircraft taxi fuel burn using flight data recorder archives from an operational fleet.

We build a model that, given the taxi trajectory of a flight (for example, from a surface surveillance system), can estimate the resultant fuel burn from observations of aircraft position, velocity and acceleration during taxiing. In addition to the

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[1] Recently Senzig et al. (2009) and Patterson et al. (2009) have shown that the ICAO estimates can be quite different from the actual fuel burn in the terminal area, which includes the fuel consumed during taxi-out, take-off, and the initial part of the climb.

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challenges associated with using the ICAO indices, pilot behavior is also a factor in determining the fuel flow rates during taxi. For example, some pilots do not reduce their engine thrust settings each time that they stop, and do not increase them when they accelerate from a stop, choosing instead to "ride the brakes". Idealized models of taxiing hence cannot capture the potentially significant effect of these subtleties. Finally, prior studies have suggested that the relationship between emissions or fuel flow rates, and engine thrust settings, is not well-understood for low thrust settings, such as those encountered during taxiing (Herndon et al., 2009). In order to overcome these challenges, this paper adopts a data-driven approach to modeling taxi fuel burn.

The flight data recorder (FDR) stores onboard measurements of key aircraft parameters. FDR archives belonging to an international airline, from over 2300 flights in the year 2004, were used in this study. The dataset included flights originating from the US, Europe, Asia and Africa. Aircraft types included in the dataset were the Airbus A320 family (A319, A320, A321), the A330 (with Rolls Royce and General Electric engines), the A340, the Avro RJ85 and Boeing's B757, B767 and B777. Of these, the A340 and the ARJ85 are 4-engined aircraft, while the others are 2-engined. A hundred and five parameters were available in the dataset, including fuel flow rates, throttle settings, velocity, position (latitude/longitude), ambient temperature and thrust. It is believed that some of these quantities, such as the thrust, were derived and not directly measured (Yoder, 2007).

The preprocessing of the data consisted of sorting flights, extracting the taxi phase, filtering the estimated velocity, and extracting events of interest such as stops and turns. The velocity as derived from position required filtering due to a low update rate (0.2 Hz) of aircraft position during taxiing. The taxi-out phase was separated by extracting the portion of the surface trajectory between the pushback from the gate and the start of the takeoff roll. Identification of pushback was carried out using a combination of fuel-flow rate and speed conditions, and the start of the takeoff roll was determined using a speed cut-off. Similarly, the taxi-in phase was extracted as the trajectory between the end of the landing roll (determined using a speed cut-off) and the end of the taxi-in process.

## 2. Characterization of the taxi process

The adoption of ICAO fuel burn indices for taxi fuel burn estimation typically requires the assumption that surface operations occur entirely at 7% thrust (power setting), and the use of the corresponding fuel flow for all calculations (International Civil Aviation Organization, 2008). In other words, the fuel burn index for taxiing is the one associated with the 7% thrust setting. The indices used in this paper were obtained from the 2010 ICAO engine database (International Civil Aviation Organization, 2010). To compare the ICAO values to actual data, the average FDR-derived fuel burn index for each available aircraft type in the dataset was calculated, by dividing the taxi-out or -in fuel burn by the taxi-out or -in time and the number of engines, and averaging this over all aircraft of a given type.

Fig. 1 shows that the ICAO fuel burn index for departures can differ from the FDR-derived value, which is consistent with the results of a previous study (Patterson et al., 2009). It is seen that for several aircraft types, the ICAO method produces an overestimate of fuel burn, which has implications for the quantification of airport emissions. The figure also shows that the average thrust values for several of the aircraft types differ significantly from the assumed 7% value. This difference in thrust settings is worth noting, since recent studies have shown that the emissions indices of some pollutants such as hydrocarbons (HCs) and carbon monoxide (CO) are highest at the lowest thrust settings (Herndon et al., 2009). Finally, while the fuel burn indices and average thrust settings are similar for arrivals and departures of a given aircraft type, they are found to be marginally higher for departures than for arrivals.

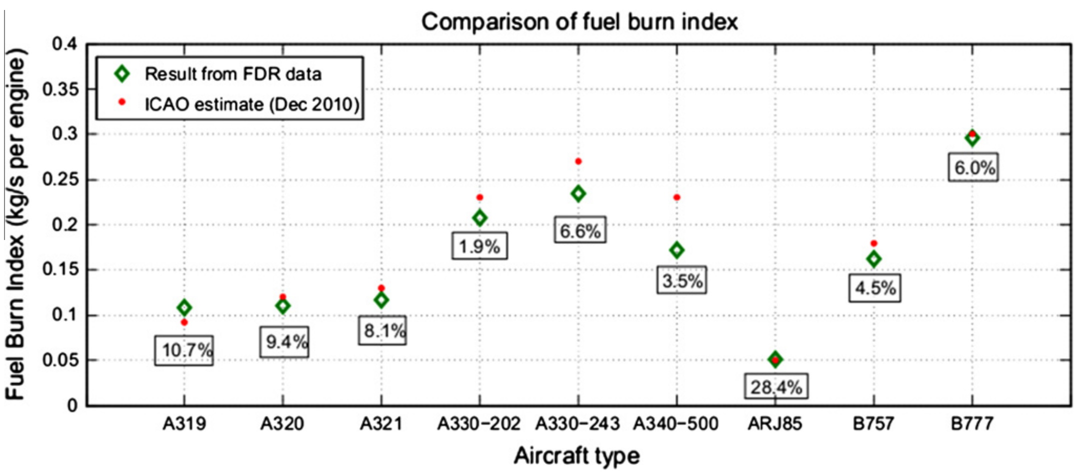


**Fig. 1.** Comparison of fuel burn indices as calculated from FDR data for departures, and the ICAO values. *Note*: The tags on the data show the average thrust during taxi-out for the corresponding aircraft type.

In general, the surface trajectory of an aircraft is composed of periods of constant velocity taxi in a straight line, interspersed by events such as stops and turns. The results of any estimation procedure that incorporates these events is likely to depend on their exact definitions, which are provided below.

The number of turns made by an aircraft taxiing on the ground was expected to affect the fuel burn, because the aircraft may slow down during its turn and speed up again after completing it, and because of the use of differential thrust for turning. A 'turn' was defined to be a heading change of at least 30° that was held over at least 30 s. Fig. 2 (left) shows the heading variation during taxi-out for a sample flight. Each time instant is tagged based on whether or not a turn has been detected to be in progress.

The number of stops made by aircraft was also expected to be a determinant of fuel burn, because of the throttle adjustments necessary during the stopping and restarting process. Usually, an aircraft has to stop during a handoff from one ground controller to another, because there is passing traffic on an intersecting taxiway/runway, or in the runway departure queue. There are two ways in which an aircraft can be brought to a halt: one way is to apply the brakes while reducing the thrust to idle, and the other is to apply the brakes while keeping the thrust constant. There is a fuel burn tradeoff involved with both methods. Reduction of the thrust while stopping reduces fuel consumption if the duration of the stop is long. However, thrust has to be increased to start taxiing again (breakaway power), and this is accompanied by a spike in the fuel consumption. Also, aircraft engines exhibit some time lag while spooling up, leading to slow response times when starting from a standstill. On the other hand, if the aircraft is stopped using only brakes, the fuel flow rate remains high, and can lead to significantly higher burn if the stop is prolonged. However, there is a performance benefit on restart. Consequently, pilots tend to use one of the two methods depending on personal preference and operational considerations. In this study, an aircraft was defined to have stopped during its taxi phase if its velocity dropped and stayed below a stop threshold of 2.25 m/s for at least 20 s, and then subsequently increased above a start threshold of 6.25 m/s. The initial pushback and engine start for departures is not counted as a stop event. Sample results from the stop detection algorithm are shown in Fig. 2 (right).

## 3. Linear models of taxi fuel burn

Two possible linear models for estimation of the taxi-out fuel burn are presented here. The first model is based on an initial hypothesis while the second incorporates lessons learned from the first model, and uses different independent variables. The parameters of both models are calculated using least-squares regression.

### *3.1. Taxi time and number of stops/turns as independent variables*

The initial hypothesis in this study was that the fuel burn on the ground would be a function of the taxi time, number of stops and number of turns made by the aircraft. It was reasonable to expect that taxi time was a determinant of fuel burn, since it is the time for which the engines are on. In addition, given that the engines run at constant thrust for a large part of the taxi process, we expect the effect of taxi time on fuel burn to be linear. Stops were expected to affect fuel burn because of the breakaway thrust required to start moving once an aircraft was stopped (Nikoleris et al., 2011). We assume that each stop adds a relatively fixed fuel penalty, resulting in a linear relationship between the number of stops and the additional fuel burn. Similarly, turns require an adjustment of the thrust setting, but assuming that the adjustment is similar for each turn, this effect would also be approximately linear (Nikoleris et al., 2011). Analysis of data from several airports has shown that taxi speeds on the surface do not vary following delays, and therefore time lost in stops cannot be made up elsewhere (Simaiakis et al., 2011). The number of stops was therefore assumed to be uncorrelated to taxi time, and the value of baseline fuel flow rate for a given flight was assumed to be constant.

Finally, Hill and Peterson (1992) and Yoder (2007) have found that engine specific fuel consumption is proportional to the square root of ambient temperature ($T_{amb}$). Therefore, the fuel burn of each flight was normalized for the effect of ambient temperature as:

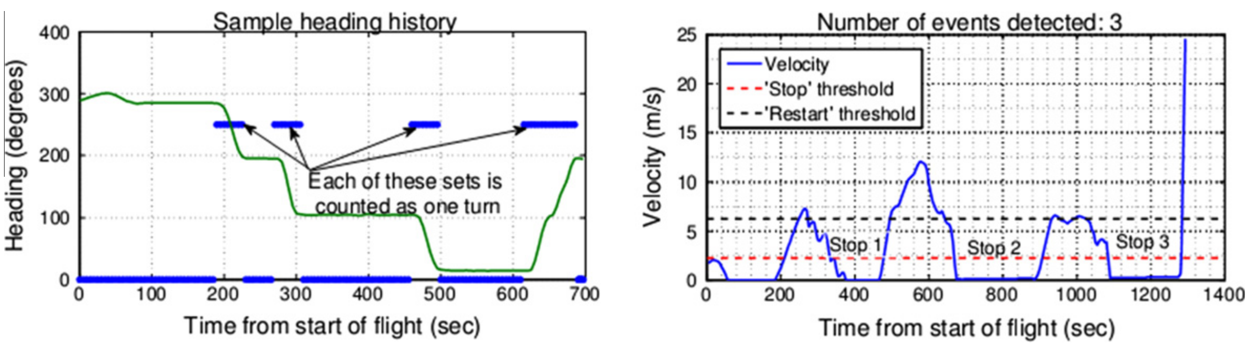


**Fig. 2.** Plot of heading history for a sample flight, showing the detected turns (left) and an example of a departing flight with three stops (right).

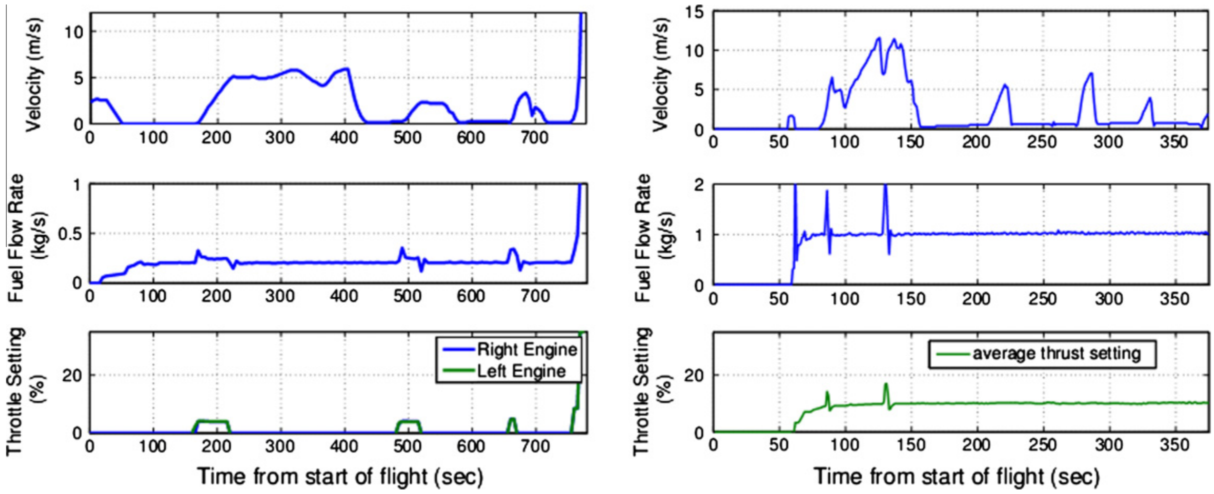


**Fig. 3.** Velocity with fuel consumption rate and engine thrust settings for a surface trajectory exhibiting increases in velocity after stops, accompanied by spikes in fuel flow rate (left) and with settings for a trajectory that exhibits no change in fuel flow rate or thrust setting for some stop events (right).

$$\frac{f}{\sqrt{T_{amb}}} = a_1 + b_1 t + c_1 n_s + d_1 n_t \qquad (1)$$

where $f$ is the fuel consumed, $t$ is the taxi time, $n_s$ is the number of stops, and $n_t$ is the number of turns made by the aircraft during taxi, while $a_1$, $b_1$, $c_1$ and $c_1$ are the parameters to be estimated. The coefficient $b_1$, is the baseline taxi fuel burn rate (normalized by $T_{amb}$) of that aircraft type.

The parameters are estimated using standard least-squares regression with outliers with unusually long taxi times ignored.[2] An upper threshold of 0.1 on the $p$-value of each parameter is used for inferring statistical significance of each variable. The main insights obtained from the parameter estimation for the above model are described below:

- Taxi-out time is the largest contributor to taxi-out fuel burn and is statistically significant.
- The statistical significance of the number of stops varies by aircraft type, being significant for only some aircraft types.
- The effect of the number of turns on total fuel burn is very small, even in comparison to the effect of the number of stops. Given the dominance of taxi time, the effect of turns on fuel burn appears to be negligible.
- The statistical significance of the number of turns also varies by aircraft type, but the significance of stops for a particular aircraft type does not appear to be related to the significance of the number of turns.

Considering specific aircraft types in more detail, as seen in Fig. 3, a start from having stopped is accompanied by a spike in fuel consumption in some cases, and but not others. This variation is noticed between flights of the same aircraft type, across different aircraft types, and sometimes even between two different stop events on the same flight. No common characteristic is found to explain these differences, although aircraft size, engine manufacturers, location of operating airports, aircraft weight class and period of initial introduction of the aircraft were considered. In addition, regarding the thrust setting profile, acceleration events after stops that are not accompanied by an increase in the fuel burn rate are not accompanied by a change in thrust setting either. The difference in results therefore seems due to differences in pilot behavior, whether reduction of thrust when stopping is more or less prevalent for the given aircraft type. A similar argument could be made for thrust characterization during turns as well.

### *3.2. Taxi time and number of acceleration events as independent variables*

Although the previous model produced reasonable estimates of the taxi-out fuel burn, the differences in statistical significance of the explanatory variables motivated the investigation of factors other than stops and turns as drivers of fuel burn. Therefore, the number of stops and number of turns were dropped as independent variables, and the number of acceleration events was in added in their place. The logic behind this decision was that fuel flow rates were seen to increase for aggressive starts from standstill, as opposed to gradual ones. One acceleration event was logged if the aircraft accelerated at more than $0.15\ m/s^2$ for at least 10 s. In Eq. (2), $n_a$ is the number of acceleration events. The other variables have the same definition as before. The resultant linear model for normalized fuel burn is:

$$\frac{f}{\sqrt{T_{amb}}} = a_2 + b_2 t + c_2 n_a \qquad (2)$$

[2] There were at most two such data-points for any type of aircraft, about 0.5% of the data.

**Table 1**
Parameter estimates and diagnostic statistics for the relationship of taxi fuel burn against acceleration events.

| Aircraft type | Constant | | Taxi time | | # Acc. Events | | Corr. |
|---|---|---|---|---|---|---|---|
| | $a_2\left(\frac{kg}{\sqrt{K}}\right)$ | $p_{a2}$ | $b_2\left(\frac{kg}{s\cdot\sqrt{K}}\right)$ | $p_{b2}$ | $c_2\left(\frac{kg}{\sqrt{K}}\right)$ | $p_{c2}$ | $\rho$ |
| *Departures* | | | | | | | |
| A319 | 0.0811 | 0.31 | 0.0122 | 0.0 | 0.0965 | 0.0004 | 0.9938 |
| A320 | −0.0896 | 0.24 | 0.0124 | 0.0 | 0.1174 | 0.0000 | 0.9924 |
| A321 | 0.0942 | 0.37 | 0.0129 | 0.0 | 0.0832 | 0.0184 | 0.9858 |
| A330-202 | 0.2904 | 0.02 | 0.0217 | 0.0 | 0.3809 | 0.0001 | 0.9816 |
| A330-243 | −0.0903 | 0.25 | 0.0265 | 0.0 | 0.1007 | 0.0312 | 0.9965 |
| A340-500 | 0.3626 | 0.10 | 0.0375 | 0.0 | 0.3984 | 0.0137 | 0.9918 |
| ARJ85 | 0.0973 | 0.00 | 0.0102 | 0.0 | 0.0366 | 0.0203 | 0.9928 |
| B757 | 0.2133 | 0.03 | 0.0173 | 0.0 | 0.0699 | 0.2007 | 0.9861 |
| B767 | 0.1584 | 0.20 | 0.0202 | 0.0 | 0.1929 | 0.0012 | 0.9795 |
| B777 | −0.1223 | 0.02 | 0.0335 | 0.0 | 0.1385 | 0.0093 | 0.9985 |
| *Arrivals* | | | | | | | |
| A319 | −0.0124 | 0.8087 | 0.0118 | 0.0 | 0.1309 | 0.002 | 0.9867 |
| A320 | −0.0706 | 0.0064 | 0.0123 | 0.0 | 0.1199 | 0.0 | 0.9951 |
| A321 | −0.0211 | 0.2914 | 0.0126 | 0.0 | 0.1544 | 0.0 | 0.9977 |
| A330-202 | −0.0702 | 0.2247 | 0.0203 | 0.0 | 0.2897 | 0.0 | 0.9883 |
| A330-243 | 0.0370 | 0.2985 | 0.0258 | 0.0 | 0.0478 | 0.0269 | 0.9973 |
| A340-500 | −0.0065 | 0.9576 | 0.0380 | 0.0 | 0.2342 | 0.0008 | 0.9920 |
| ARJ85 | −0.0118 | 0.2198 | 0.0106 | 0.0 | 0.0517 | 0.0 | 0.9890 |
| B757 | 0.3087 | 0.0 | 0.0144 | 0.0 | 0.4210 | 0.0 | 0.9656 |
| B767 | 0.4502 | 0.0 | 0.0185 | 0.0 | 0.1226 | 0.0081 | 0.9720 |
| B777 | −0.1406 | 0.0 | 0.0328 | 0.0 | 0.0898 | 0.0014 | 0.9986 |

Table 1 presents the results from parameter estimation for this model. Both the taxi time and the number of acceleration events are found to be statistically significant for all aircraft types but the Boeing 757; even for this aircraft type, the *p*-value is not very large. Fig. 4 compares the estimated taxi-out fuel burn to actual values for two aircraft types.

## 4. Results

From the model, taxi time is identified as the main driver of fuel consumption. In other words, given an accurate estimate of the fuel burn index, a good estimate of the fuel consumption of a surface trajectory can be obtained using just the taxi time. The analysis also shows that the ICAO engine databank overestimates the fuel burn indices of some aircraft types.

The FDR analysis suggests that contrary to assumptions in Jung (2010), stops or turns by themselves may not necessarily result in an increase in fuel burn rate, and therefore do not provide much information beyond additional taxi time. It is

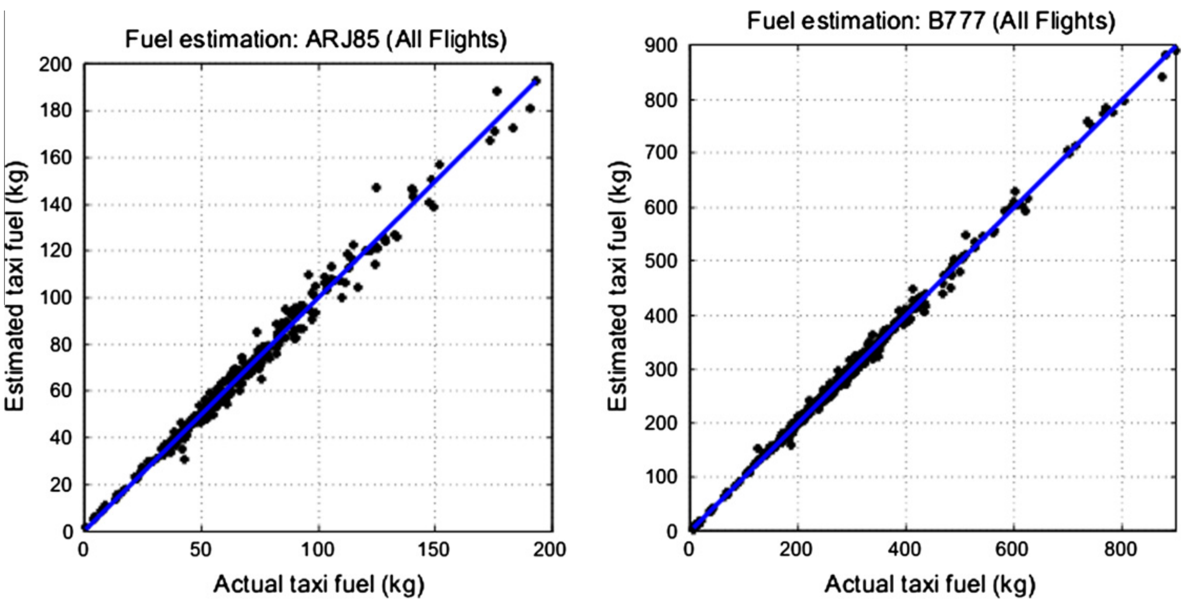


**Fig. 4.** Estimated versus actual taxi-out fuel burn for the (left) Avro-RJ 8 and Boeing 777 (right) with the taxi-out times and number of acceleration events as independent variables.

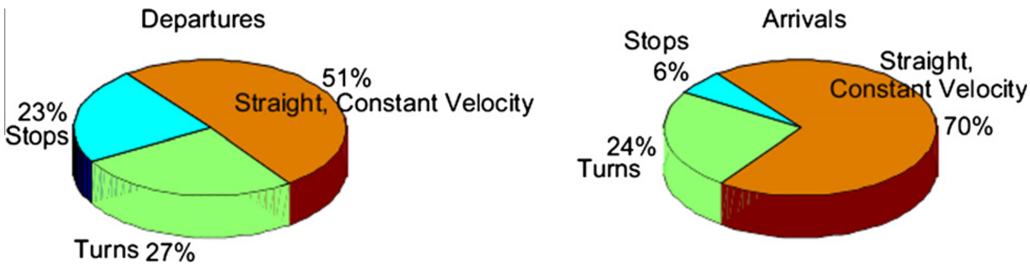


**Fig. 5.** Fuel consumption by mode of taxiing.

conjectured that this can be explained by the variability in pilot behavior (since there may not be thrust changes accompanying stops or turns), the inherent variability in the thrust settings during taxi (which may be significantly different from the ICAO 7% assumption), and the dominance of the taxi time as the driver of taxi fuel burn. However, acceleration events (defined as the aircraft accelerating at more than 0.15 $m/s^2$ for at least 10 s) have a small but statistically significant impact on the taxi fuel burn. The inclusion of these effects will provide a more accurate estimate of surface fuel consumption, and will also need to be considered in surface traffic optimization studies.

The analysis of FDR data can also be used to estimate approximately the percentage of fuel burn corresponding to straight taxi at constant speed, turns, and stops on the surface. In contrast to physics-based models, this analysis accounts for pilot behavior and thrust settings during stops and turns. The results are shown in Fig. 5, for departures and arrivals. The data spans many airports across several continents, and therefore provides an aggregate estimate. The results vary depending on individual airport layout, level of congestion, operational procedures, etc. but indicate that on average, 70% of arrival fuel burn corresponds to the normal taxi mode, as compared to only 51% for departures. By contrast, only 6% of arrival fuel burn corresponds to stops, as compared to 23% for departures. The impact of turns is similar for arrivals and departures. This supports the notion that due to the prioritization of arrivals, departures at busy airports suffer a large proportion of the effects of congestion.

## 5. Conclusions

This paper presented a linear model for estimating the taxi-out fuel consumption corresponding to an aircraft trajectory, based on the taxi time and number of acceleration events. The model parameters were determined using FDR data, and the proposed model was shown to provide more realistic estimates of fuel burn than ICAO fuel burn indices, or other dynamics-based approaches for translating surface trajectories to fuel burn.

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