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Characterising the Variability in Taxiway Turns of Regional Airliners using Air Traffic Data

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Abstract

To support the growth of structural health monitoring for aircraft landing gear, Automatic Dependent Surveillance-Broadcast (ADS-B) trajectories have been exploited to characterise the variability in aircraft ground turns. This paper extends prior work through consideration of turboprop, regional jets and large regional jets. The characterisation of ground turning manoeuvres has highlighted that regional turboprops are exposed to increased rates of fatigue-critical tight turns and that the geographical location of regional jets impacts turn occurrences. Finally, it has been observed that individual aircraft within the regional jet fleet can demonstrate significantly higher rates of tight turns compared to the overall fleet.

1. Introduction

Aircraft landing gear are exposed to a significant range of ground turning manoeuvres, including high-speed runway exits and low-speed pivot turns during taxi.[1,2] These ground turning manoeuvres result in cyclic loads being applied to landing gear structures, ultimately resulting in fatigue damage accumulation across the design life of the landing gear.[3] As a result, there has been sustained research into landing gear manoeuvre occurrences and routes towards structural health monitoring.[4–6]

Structural health monitoring approaches for landing gear are reliant on access to flight recorder data[5,7,8] or additional instrumentation of landing gear,[9] which can require significant engineering effort and resource to realise. When coupled to the significant variability present in the ground manoeuvres that aircraft perform during taxiing,[4] there is a need to generate initial data to justify the implementation, and focus of, structural health monitoring systems.

To support activities relating to the development of structural health monitoring for aircraft landing gear, there has been continued work on exploiting air traffic data, specifically Automatic Dependent Surveillance-Broadcast (ADS-B) trajectories for identifying and characterising aircraft ground manoeuvres during taxi.[2,4,10] ADS-B trajectories provide aircraft position reports (latitude, longitude and altitude)[4] and ADS-B data is collated for individual aircraft under repositories such as Flightradar24,[11] enabling historic trajectories to be accessed and processed.

Beyond initial work that employed ADS-B to characterise top-level ground manoeuvres across global widebody and narrowbody fleets,[2,4] ADS-B trajectories have also been employed to characterise 'bump' loads resulting from surface roughness.[10] Concerning fatigue-critical landing gear ground manoeuvres, prior work has also investigated the characterisation of ground turns present within ADS-B trajectories, to identify 'tight' or 'pivot' turns.[4] There has also been growing interest in the enhancement of ADS-B ground trajectories through filtering and alignment to known airport geometries to mitigate often noisy and low-resolution ADS-B ground trajectories.[12]

Whilst prior work has focused on widebody and narrowbody aircraft fleets,[2,4] there has only been limited research into the ground trajectories of regional aircraft, typically defined as aircraft up to 100 passengers.[13,14] However, recent trends in the aerospace sector have also seen regional jet families offering "stretch" variants, leading to passenger capacities that rival the smallest narrowbody aircraft.[13,14] ADS-B ground trajectories have been recently employed by Taltaud et al. to develop the requirements for electric taxiing systems for regional turboprop aircraft.[15] Within this work, taxi distances, speeds and accelerations were derived from 200 ADS-B trajectories, highlighting the availability of ADS-B ground trajectories for regional aircraft.[15] Furthermore, prior work concerning the ground manoeuvres performed by narrowbody aircraft has proposed that the variability in such manoeuvres may be impacted by the geographical location of an aircraft's operational base.[4]

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Consequently, this paper aims to characterise the turning manoeuvres present within the ground trajectories of regional airliners, including turboprop, regional jet and large regional jet aircraft along with investigating geographical impacts on the turning manoeuvres of such aircraft.

2. Methodology and Dataset

In order to explore the variability in ground turning manoeuvres performed by regional airliners, historic ADS-B trajectories for regional airliners were sourced from Flightradar24[11] and were coupled with a pre-existing methodology for identifying and characterising taxiway turns within ADS-B trajectories.[4] An example of a selected pre-takeoff ADS-B trajectory is shown in Figure 1. This section will briefly detail the existing ADS-B processing methodology and the approach used to compile a dataset of ADS-B trajectories across regional turboprop and regional jet aircraft fleets accounting for different geographical operating locations.

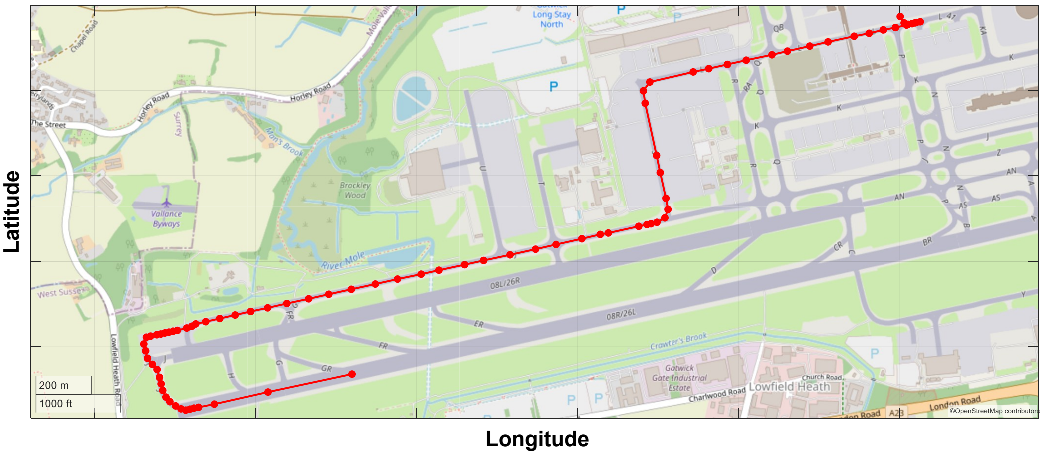

Figure 1: An example of a pre-takeoff taxi phase ADS-B ground trajectory. ADS-B data from Flightradar24.[11] Map data from OpenStreetMap (*https://www.openstreetmapt.org/copyright*).

The identification of turning manoeuvres within ADS-B ground trajectories can be robustly achieved through identifying changes in the bearing ‘$\Delta\alpha$’ between consecutive latitude and longitude positions, as detailed in prior work.[4] Consecutive positive changes in the bearing ‘α’ between the aircraft position are grouped into a right turn, and consecutive negative changes in the bearing identify a left turn, as shown in Figure 2. The use of latitude and longitude positions to identify turns, compared to the reported aircraft heading within the ADS-B data permits the removal of ‘false’ turns that originate from jumps in the ADS-B trajectory.[2,4]

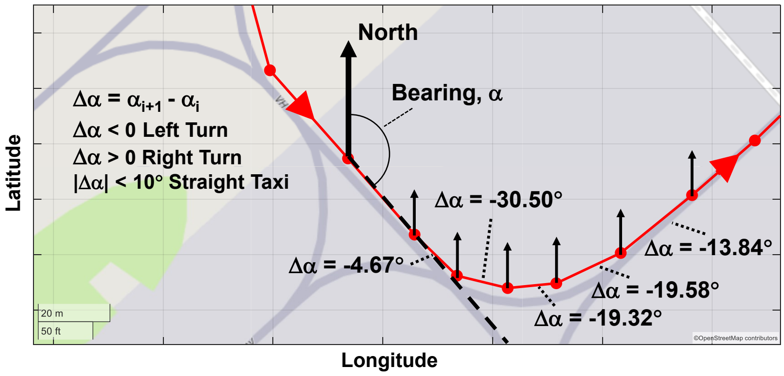

Figure 2: Identification of ground turn direction using bearing between ADS-B trajectory points as defined in prior work.[4] ADS-B data from Flightradar24.[11] Map data from OpenStreetMap (*https://www.openstreetmapt.org/copyright*).

The employment of latitude and longitude data also permits geospatial characteristics of the turns to be estimated, including the turn radius along with estimated turn rates, both in temporal and spatial domains.[4] Previous work has highlighted that the maximum spatial turn rate ‘$\Delta\theta_{s,max}$’ observed within a turn can be employed to distinguish between

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standard and tight or ‘pivot’ turns,[4] whereby the spatial turn rate ‘$\Delta\theta_s$’ between two consecutive aircraft positions is computed as the change in bearing ‘$\Delta\alpha$’ divided by distance between the two consecutive positions.[4]

Figure 3a) and b) demonstrate example observed spatial turn rates for a standard and tight turn observed within an ADS-B trajectory. It can be see that the maximum spatial turn rates observed for standard turns are expected to be lower than those observed for tight turns, and prior work has proposed that the threshold between standard and tight turns is $\Delta\theta_{s,max}$ = 2.33°/m for narrowbody aircraft.[4]

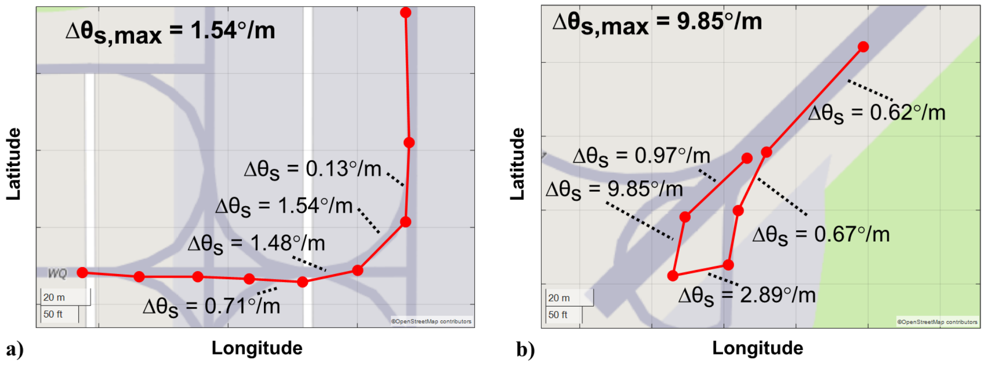

Figure 3: Examples of observed spatial turn values, $\Delta\theta_s$ and $\Delta\theta_{s,max}$ for a) standard and b) tight ground turns. ADS-B data from Flightradar24.[11] Map data from OpenStreetMap (*https://www.openstreetmapt.org/copyright*).

2.1 Compilation of Ground Trajectories

The assembly of the aircraft ground trajectories was performed through random sampling across the period of one year, from March 2024 to March 2025. The aircraft fleet lists available from Flightradar24[11] were complied into global turboprop, global regional jet (up to 100 passenger seats) and global large regional jet (typically 100-120 passenger seats) categories.

As the capture of ADS-B trajectories is reliant on line-of-sight, there are specific global locations and airports that do not currently have sufficient ground coverage to capture aircraft taxi routes via ADS-B. Consequently, only aircraft from North America and Europe were retained within the fleet lists, due to the increased ADS-B ground coverage available in these locations. Unfortunately, turboprop operations in North America with ground trajectories of sufficient quality were limited to a small range of operators and therefore were not included within this study.

Prior work that utilised ADS-B ground trajectories for regional airliners[15] employed a sample size of 200 trajectories and consequently, a sample of 200 flights for each regional aircraft type was collected, evenly distributed across geographical locations as shown in Table 1.

Table 1: Regional airliner fleets included within the study.

	Sample Size	
	North America	Europe
Turboprops	-	200
Regional Jets	100	100
Large Regional Jets	100	100

For each of the five fleets shown in Table 1, flights were randomly sampled to the required sample size, by randomly sampling an aircraft registration from a fleet list, and then randomly sampling a month, day and sector leg flown by the aircraft.

When sampling a flight, the ground trajectory was visually inspected to ensure it was complete and in the event the ground trajectory was not complete, the chronologically nearest flight was selected. The trajectories were each processed using the methodology described in Section 2 and statistics relating to the number of turns per taxi phase and the characteristic of each identified turn were generated. As this study is concerned with taxi phases only, trajectory elements related to pushback, if present in the trajectory, were removed.

It is important to note that the term “fleet" within this paper refers to the aggregation and classification of individual registered airframes into the categories shown in Table 1 and does not constitute the fleet of a single operator or aircraft type.

3. Results

This section will present and contextualise the results from applying the ground turn identification and characterisation methodology to the assembled ADS-B trajectories for the fleets shown in Table 1.

3.1 Turn Occurrence Rates

The first selection of statistics generated from processing the ADS-B ground trajectories concerns the number of turns performed by regional airliners within the pre-takeoff and post-landing phases. The variability in the number of pre-takeoff and post-landing turns per-flight can be visualised using histograms and further decomposed from the top-level aircraft type fleets, into fleets operating within the North American and European geographical locations. Whilst the histograms have been limited to a maximum of 20 turn occurrences to support readability, it should be noted that two flights associated with the North American large regional jets exceeding this value with 22 and 23 post-landing turns.

The histograms shown in Figure 4a) and 4b) show the variability in the number of pre-takeoff and post-landing turns for the overall turboprop, regional jet and large regional jet fleets. From Figure 4a) it can be observed that all regional aircraft types demonstrate a mode number pre-takeoff turns of four, with differing levels of variability. The proportion of flights with a greater number of pre-takeoff turns than the observed mode was 37%, 51% and 45% for the turboprop, regional jet and large regional jet fleets respectively. This suggests that regional jets will have a higher level of variability in pre-takeoff turn occurrences and this is expected to be due to turboprops operating from smaller and therefore potentially simpler, airport geometries.

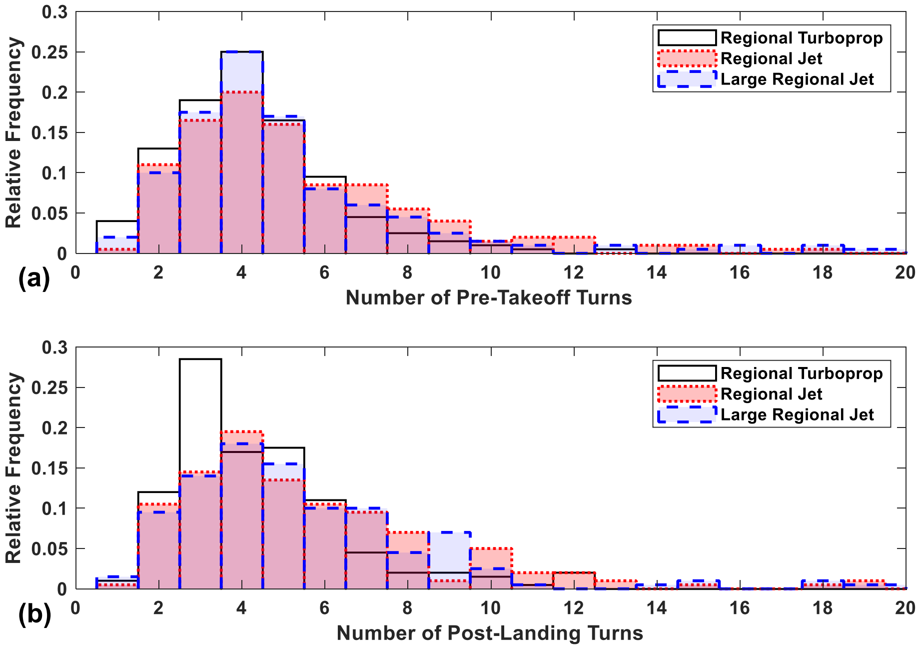

Figure 4: Histograms of per-flight (a) pre-takeoff turn occurrences and (b) post-landing turn occurrences for turboprop, regional jet and large regional jet aircraft.

Different trends can be observed for the post-landing phase in Figure 4, where the mode number of turns is three for the turboprop fleet and four for regional jet aircraft. For the post-landing phase, the turboprop fleet also demonstrates increased variability, with 58% of flights having more than the mode number of post-landing turns, whilst this value is consistent for regional jets and large regional jets at 54%. Consequently, it can therefore be observed that the type of regional airliner impacts the occurrence of ground turning manoeuvres and that these trends are also different depending on the taxi phase being performed.

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The histograms shown in Figure 4 can be further decomposed for the regional jet and large regional jet fleets into aircraft fleets aligned with either the North American or European geographical location of operation. Figure 5a) demonstrates that there are significant differences in the variability in pre-takeoff turn occurrence rates between regional jets operating in North America and Europe, with North American jets demonstrating a mode of five turns per-flight and European jets demonstrating a mode of four. Whilst both fleets show that approximately 40% of flights exceed the mode number of pre-takeoff turns, it can be observed from Figure 4a) that a flatter distribution shape occurs for the North American fleet, inferring an increased occurrence of flights with higher numbers of pre-takeoff turns. The difference between the North American and European regional jet fleets is expected to be as a result of North American airports typically having larger and more complicated geometries compared to European airports.[16]

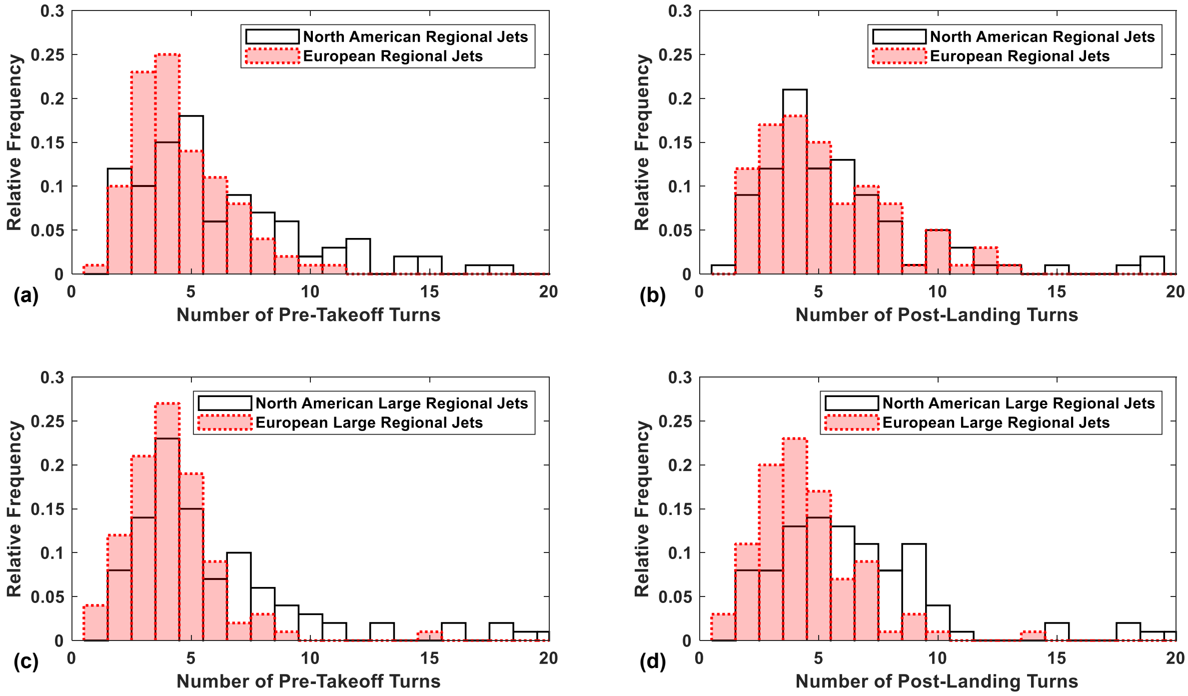

Figure 5: Geographical impact on (a) pre-takeoff and (b) post-landing turn occurrences for regional jets and geographical impact on (c) pre-takeoff and (d) post-landing turn occurrences for large regional jets.

Concerning the post-landing taxi phase for regional jet aircraft, it can be observed from Figure 5b) that both the North American and European jet fleets present similar variability in the number of post-landing turns. This observation suggests that the impact of North American airport geometries may only impact regional jets during the pre-takeoff taxi out to the runway and that post-landing taxi routes may be more direct to the aircraft parking location after vacating the runway.

Figure 5c) demonstrates that both the North American and European large regional jet fleets have a mode of four. However, the level of variability between the two different geographical fleets is seen to differ, with 55% of North American flights exceeding the mode compared to only 35% of European flights. This differential is expected to again be the result of more complex airport geometries in North America.

A similar trend is present for the post-landing taxi phase for large regional jets, where European aircraft are shown to have a lower mode number of post-landing turns per-flight as shown in Figure 5d). A similar proportion of flights were observed to exceed the mode as for the pre-takeoff phase, with 56% and 39% of flights exceeding the mode number of post-landing turns for the North American and European large regional jet fleets respectively.

It is interesting to note that when comparing Figure 5b) and Figure 5d) that whilst the post-landing taxi phase of regional jets is insensitive to the geographical location, the same is not observed for large regional jets. This is proposed to be a result of North American regional jets operating at smaller airports with similar characteristics to European airports, whilst large regional jets may be focused on operations from larger North American airports. Alternatively, smaller regional jets may be able to vacate the arrival runway at an earlier point than large regional jets, which could lead to a more direct taxi routing to the arrival stand.

Across the fleets shown in Table 1, an approximately equal share between left and right turns was observed for both the pre-takeoff and post-landing phases. This observation is consistent with prior work concerning operational loads monitoring of regional aircraft[17,18] and the processing of ADS-B trajectories for narrowbody and widebody aircraft.[2,4]

During the processing of the ADS-B trajectories, the average observed ground speed within each identified turn was also recorded in knots (Kn). Figure 6 shows histograms relating to the average observed ground speed during turns for all of the regional airliner fleets. It can be observed across all of the histograms in Figure 6 that the magnitudes and variability of taxi speed during turns were consistent across all types of regional airliner. The only deviation from this observation can be seen in Figure 6c) and Figure 6f) where North American regional jets and North American large regional jets have slightly lower taxi speeds during turns in the pre-takeoff and post-landing phases respectively. When comparing the magnitude of the speeds observed in Figure 6, it can be seen that the average speed during turns is approximately 5-10 Kn lower than the maximum taxi speeds observed in prior analysis of turboprop taxi speeds present in ADS-B trajectories.[15]

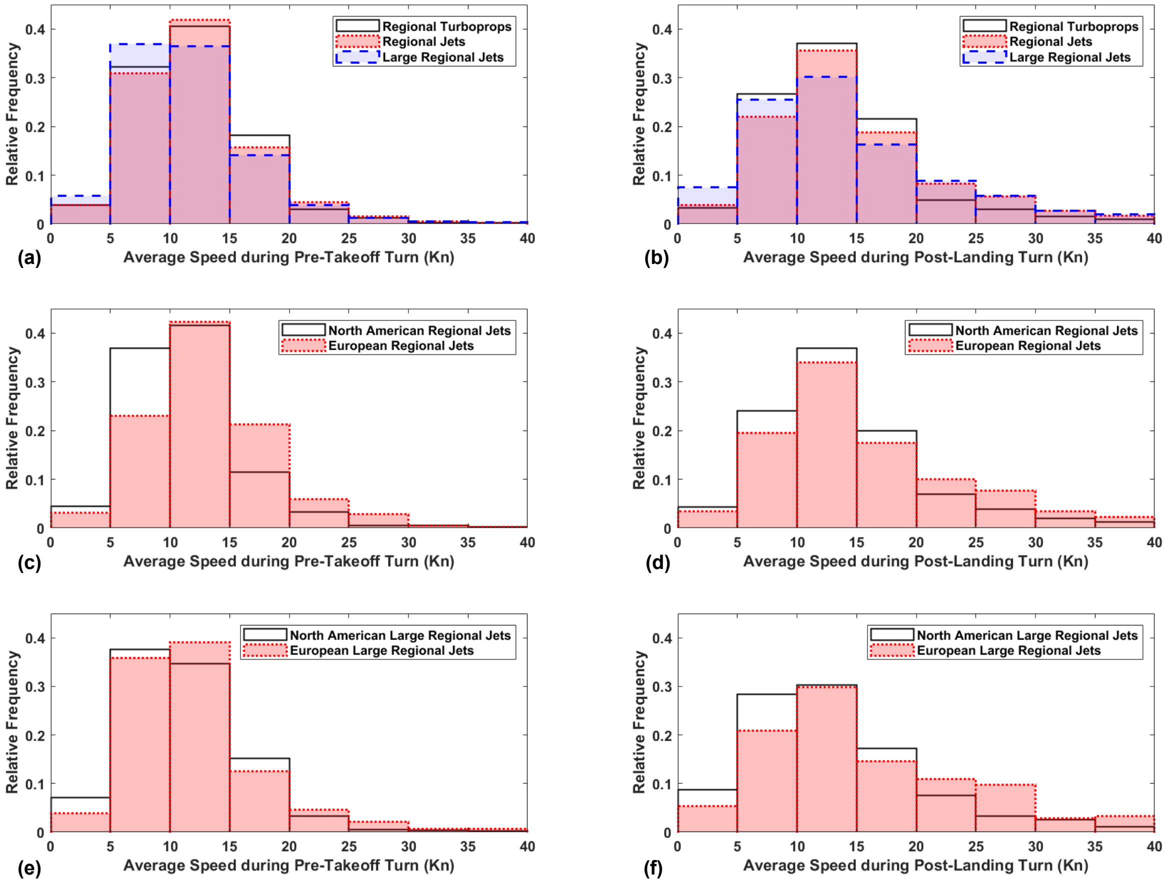

Figure 6: Average taxi speeds during turns for regional airliners (a) pre-takeoff and (b) post-landing taxi phases, geographical impact on average taxi speeds during turns for regional jets (c) pre-takeoff and (d) post-landing taxi phases and geographical impact on average taxi speeds during turns for large regional jets (e) pre-takeoff and (f) post-landing taxi phases.

3.2 Occurrence rates of Fatigue Critical Turning Manoeuvres

As highlighted in Section 1, fatigue-critical tight or pivot turns, can also be identified within ADS-B ground trajectories. As described in Section 2, tight or pivot turns can be identified based on the maximum spatial turn rate $\Delta\theta_{s,max}$ observed within a turn. Based on the procedure defined in prior work,[4] 20 examples of tight and pivot turns were identified for turboprop, regional jet and large regional jet aircraft and the maximum spatial turn rate was computed for each turn. The lower bound, defined as the 5th percentile of the $\Delta\theta_{s,max}$ related to a tight turn was found to be consistently $\Delta\theta_{s,max} = 2.6°/\text{m}$ across all regional aircraft types.

Application of the tight turn threshold to all observed turns in each fleet resulted in the tight turn occurrence rates shown in Table 2, expressed as a percentage of observed turns and also the average occurrence rate per 10 flights for

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both pre-takeoff and post-landing phases. From Table 2 it can be observed that regional turboprops perform a higher number of fatigue-critical tight turns compared to regional jets, especially for the post-landing taxi phases, where the occurrence rate is double that of the regional jet fleets. This is expected to be as a result of turboprops routinely operating from small airports that may have tight runway entry turns, or the need to backtrack the runway both prior to takeoff and after landing.

Table 2: Occurrence rate of tight turns for regional airliner fleets.

	Pre-Takeoff Tight Turns		**Post-Landing Tight Turns**	
	% of Turns	per 10 flights	% of Turns	per 10 flights
Turboprops	14.9	6	12.4	6
Regional Jets	8.5	5	5.6	3
North American Regional Jets	*6.8*	*4*	*4.0*	*2*
European Regional Jets	*10.7*	*5*	*6.1*	*3*
Large Regional Jets	8.6	4	5.1	3
Large North American Regional Jets	*8.2*	*5*	*4.1*	*3*
Large European Regional Jets	*9.2*	*4*	*6.7*	*3*

When comparing the results presented in Table 2 to the tight turn occurrence rates for narrowbody aircraft identified in previous work,[4] it can be observed that turboprop regional aircraft are consistent with narrowbody aircraft, whilst regional jets and large regional jets have a lower occurrence rate of tight turns. Whilst such a result may contradict the expectation that regional aircraft will routinely operate into small airports and hence would see tighter turns on a more frequent basis, it is important to note that there is often overlap in the airports served by regional and narrowbody aircraft.[19,20] As aircraft of differing physical sizes and landing gear track widths will operate from airports of the same geometry, taxiway turns that would be classified as ‘tight’ for a narrowbody aircraft would not be identified as tight turns for a smaller regional aircraft.

Table 2 further demonstrates that the geographical location only marginally increases the average number of tight turns performed per 10 flights, with European regional jets and large regional jets showing an increased number of pre-takeoff tight turns. This observation is expected to be as a result of smaller European airport geometries, and the reduced sensitivity of tight turn occurrence to geographical location infers that tight turns occur for manoeuvres that are required regardless of airport geometry, such as the runway entry turn and turn onto the parking stand. Whilst the majority of fleets showed an approximately equal proportion of left and right tight turns, both the post-landing tight turns of the North American regional jets and pre-takeoff tight turns of North American large regional jets were found to consist of 60% left turns.

When considering tight taxiway turns, 180° pivot turns, typically performed as turn on the runway following or preceding a backtrack, are of specific interest during fatigue analysis due to the increased torsional loads experienced on the main landing gear on the ‘inside’ of the turn as this is often braked and stationary during the pivot.[21] Consequently, the identified tight turns across the fleets were reviewed and those with a turn angle exceeding 135° were assumed to be pivot turns. The threshold of 135° was selected as the midpoint between 180° and 90°, as 90° is the angle of a typical runway entry turn or non-rapid exit taxiway turn off of a runway. The resulting occurrence rate of 180° pivot turns are shown in Table 3 and it can be observed that the occurrence rates are similar across all regional aircraft types and do not show consistent sensitivity to geographical location.

Table 3: Occurrence rate of 180° pivot turns for regional airliner fleets.

	Pre-Takeoff 180° Turns		**Post-Landing 180° Turns**	
	% of Tight Turns	per 10 flights	% of Tight Turns	per 10 flights
Turboprops	47.6	3	42.5	2
Regional Jets	45.6	2	37.5	1
North American Regional Jets	*41.5*	*2*	*37.5*	*1*
European Regional Jets	*49.0*	*3*	*37.5*	*2*
Large Regional Jets	56.8	3	38.6	1
Large North American Regional Jets	*56.0*	*3*	*46.4*	*1*
Large European Regional Jets	*57.9*	*2*	*31.0*	*1*

An additional ground turning manoeuvre of interest during the fatigue design of landing gear are s-turns, when a turn of a given direction is followed immediately by a turn in the opposite direction, as the loads applied to the landing gear are fully-reversed, increasing fatigue damage accumulation. Within the ADS-B ground trajectories for the regional airliner fleets, s-turns or 'turn-reversals' could be identified by two consecutive turns with differing turn directions. All fleets demonstrated turn reversal rates of between 26% and 36% within both the pre-takeoff and post-landing taxi phases, consistent with the values observed for narrowbody aircraft in prior work.[4] The minimum turn reversal rate was observed for the turboprop fleet, whilst the maximum values were observed for the European regional jet fleet and the North American large regional jet fleet, all within the pre-takeoff taxi phase.

3.3 Taxi Distances

Beyond ground turning manoeuvres, the taxi distance performed by aircraft in-service can also impact the fatigue design of landing gear due to the presence of 'bump' loads resulting from taxiway surface roughness, along with potentially increasing the number of braking and acceleration cycles the aircraft will perform whilst taxiing.[21] Whilst prior work has considered the variability in taxi distance across a global turboprop fleet using ADS-B trajectories,[15] the trajectories used for generating the turn occurrence statistics were also assessed to identify variability in taxi distances for all regional airliner types.

The overall taxi distance in the pre-takeoff and post-landing taxi phases was estimated as the summation of the distance between each consecutive position in the ADS-B trajectory. The pre-takeoff taxi distances for turboprop, regional jets and large regional jets are shown in Figure 7 and it can be observed that regional turboprops typically have lower taxi distances than regional jets, which are consistent regardless of the size of the regional jet. A similar observation can be made regarding post-landing taxi distances as seen in Figure 7, albeit that post-landing taxi distances are typically shorter than pre-takeoff taxi phases. It is interesting to note that whilst the presented dataset consists of only North American and European turboprops, the values presented are consistent with the values observed for a global turboprop fleet by Tatltaud et al.[15] Whilst the histograms have been limited to 8,000m for readability, it should be noted that two flights in the North American regional jet dataset were observed to have post-landing taxi distances of ≈10,000m.

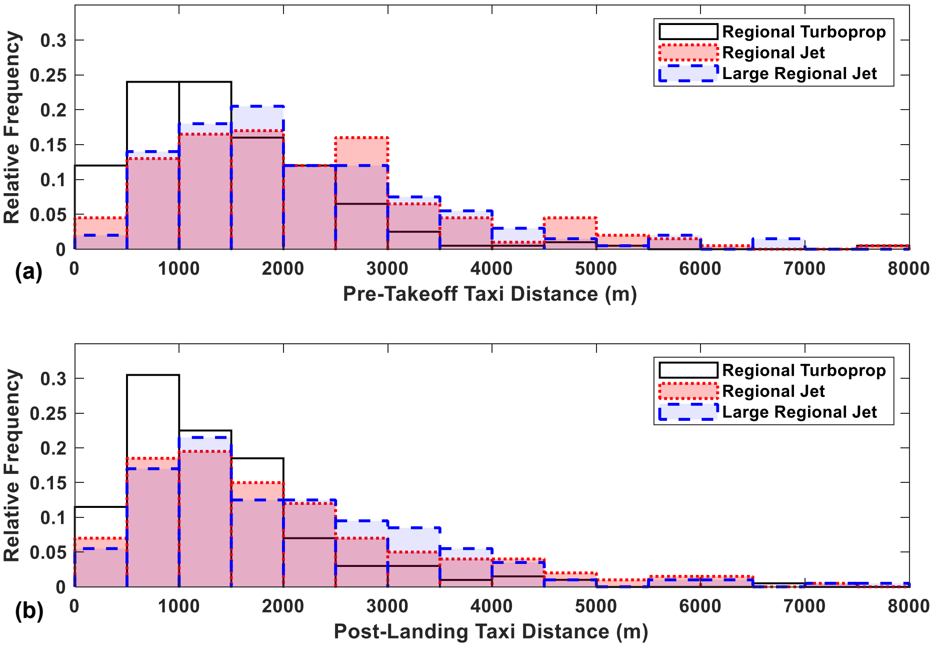

Figure 7: Variation in taxi distances for regional airliners across (a) pre-takeoff and (b) post-landing taxi phases.

The histograms shown in Figure 8 show the impact of geographical location on the taxi distances for regional jets and large regional jets. Overall, it can be observed across Figure 8 that European-based aircraft will have shorter taxi distances than North American-based aircraft and this is especially noticeable in Figure 8c) and 8d) for large regional jets. The pre-takeoff taxi distances for regional jets shown in Figure 8a) show that they are less sensitive to geographical impacts overall, but the large peak between 2,500m and 3,000m suggests the specific route networks of operators will impact taxi distances as a result of operator hubs or aircraft bases.

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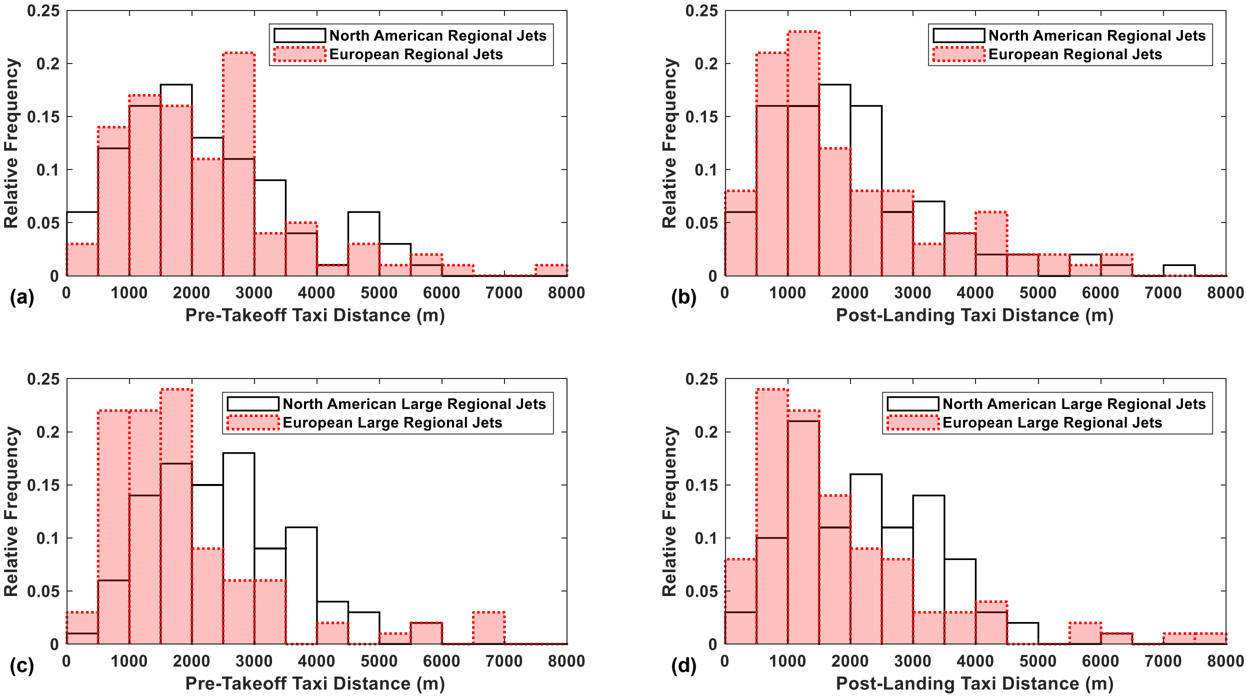

Figure 8: Geographic impact on (a) pre-takeoff and (b) post-landing taxi distances for regional jets along with geographic impact on (c) pre-takeoff and (d) post-landing taxi distances for large regional jets.

3.4 Impact of Operator Route Network

As an extension to the observation regarding European regional jets pre-takeoff taxi distances, coupled with prior studies into the impact of operator characteristics on the taxiway turn manoeuvres of narrowbody aircraft,[4] an investigation was conducted into the impact of an individual operator's characteristics on the turning manoeuvres of regional aircraft.

From reviewing route networks of regional jets, an operator was identified that has a hub and operational base which requires aircraft to perform a tight turn onto the arrival stand and then a tight turn off the departure stand, without use of a pushback tug. As it was hypothesised that such an operator characteristic would impact the tight turn occurrence rates for an individual regional jet within the operator fleet, approximately 200 ADS-B trajectories across consecutive flights for an individual regional jet were sourced from Flightradar24.[11] Based on the aircraft's utilisation, 200 flights corresponded to approximately two months of operation and consequently, the flights were sourced from one summer and one winter month of operation to capture seasonal variability in the operator's route network.

Processing of manoeuvres related to departure from and arrival on stand can be challenging due to noise and limited fidelity in data in the proximity of airport parking locations[22] and the segmentation of ADS-B trajectories into separate flights in data repositories. However, it was observed that through identifying the final three ADS-B position reports of an arrival onto the stands requiring a tight turn and applying these to the start of the next consecutive flight, along with applying the first three ADS-B position reports for a departure from the aircraft stand to the end of the preceding flight, would permit the tight turns related to the aircraft parking location to be captured.

The ADS-B trajectories for the ≈200 flights were processed using the methodology defined in Section 2 and the resulting occurrence of turns are shown in Figure 9, compared to an overall dataset consisting of all regional jets and all large regional jets included in Table 1. It can be observed from Figure 9a) that the individual regional jet has a lower mode number of pre-takeoff turns compared to the overall regional jet dataset and also shows a significantly increased proportion of flights with only one pre-takeoff turn.

The observed trend for the pre-takeoff taxi phase is further exacerbated in the post-landing phase as shown in Figure 9b), whereby the individual regional jet is observed to perform fewer post-landing turns than the overall regional jet fleet. Consequently, Figure 9 demonstrates that individual aircraft within a fleet based upon aircraft type can deviate from the occurrence and variability observed at the fleet-level.

The turns identified for the individual regional jet aircraft were also characterised as tight turns if they exceeded the $\Delta\theta_{s,max}$ threshold defined in Section 2. Table 4 shows the occurrence rate of tight turns for the individual regional aircraft, both as a percentage of turns performed and the occurrence rate per 10 flights.

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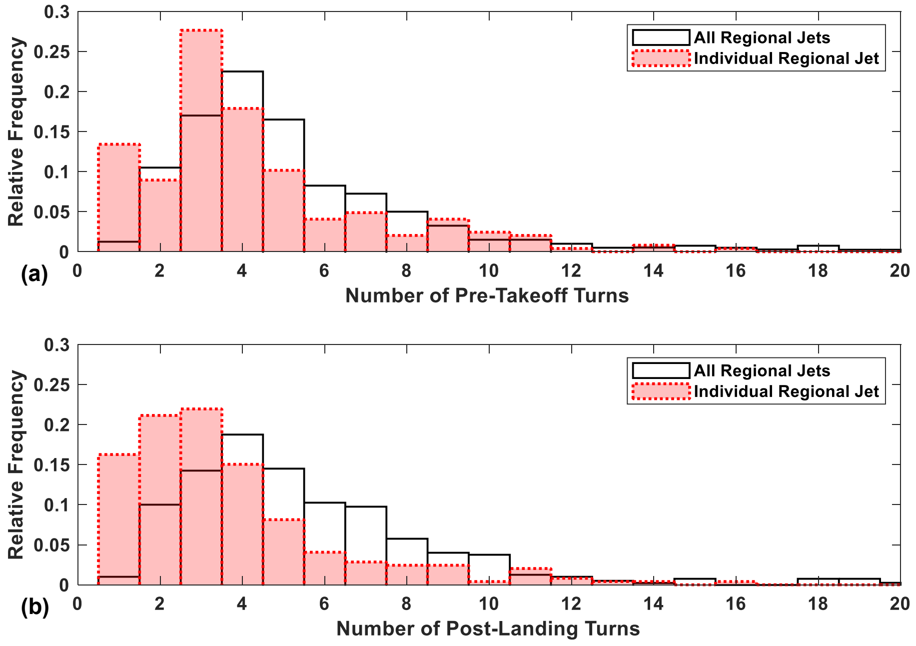

Figure 9: Histograms of per-flight (a) pre-takeoff turn occurrences and (b) post-landing turn occurrences for the overall regional jet fleet and an individual regional jet.

Table 4: Occurrence rate of tight turns for the overall regional jet fleet and an individual regional jet.

	Pre-Takeoff Tight Turns		**Post-Landing Tight Turns**	
	% of Turns	per 10 flights	% of Turns	per 10 flights
All Regional Jets	8.5	5	5.1	3
Individual Regional Jet	24.7	13	23.2	11

From Table 4 it can be seen that the individual regional jet performs a significantly higher number of tight turns than the overall regional jet fleet, with a per 10 flight occurrence rate of approximately three times that of the overall fleet. The results in Table 4 therefore demonstrate the impact of the aircraft parking arrangements that result from the route network of the aircraft's operator.

Finally, the taxi distances were estimated from the ADS-B trajectories of the individual regional jet and are shown in Figure 10a) and 10b) for the pre-takeoff and post-landing phases respectively. From Figure 10a) it can be observed that the individual regional jet has pre-takeoff taxi distance characteristics more similar to the turboprop fleet shown in Figure 7a), compared to the overall regional jet fleet. The individual regional jet also shows significantly shorter post-landing taxi distances compared to the overall regional jet fleet, as shown in Figure 10b). Whilst the histograms have been limited to 8,000m for readability, it should be noted that the individual regional jet aircraft dataset showed three pre-takeoff taxi phases and three post-landing taxi phases with distances in the range of 8,000m to 10,000m.

Consequently, the results presented within this section have shown that the characteristics of the route network and operational base of an individual regional aircraft can cause significant differences in occurrence, variability and severity of taxiway turns performed by an aircraft in-service, compared to the overall aircraft type fleet. As a result, these observations further support the continued interest in the development of structural health monitoring for individual landing gear assemblies[5] and the consideration of bespoke fatigue spectra that account for operator characteristics as previously proposed in prior work.[4]

4. Discussion

The results presented in the previous section have shown that the ground turning manoeuvres of regional airliners show significant per-flight variability, which would need to be accounted for in the generation of fatigue loading spectra for aircraft landing gear. Across the results, it has been observed that regional aircraft type does impact the occurrence rate

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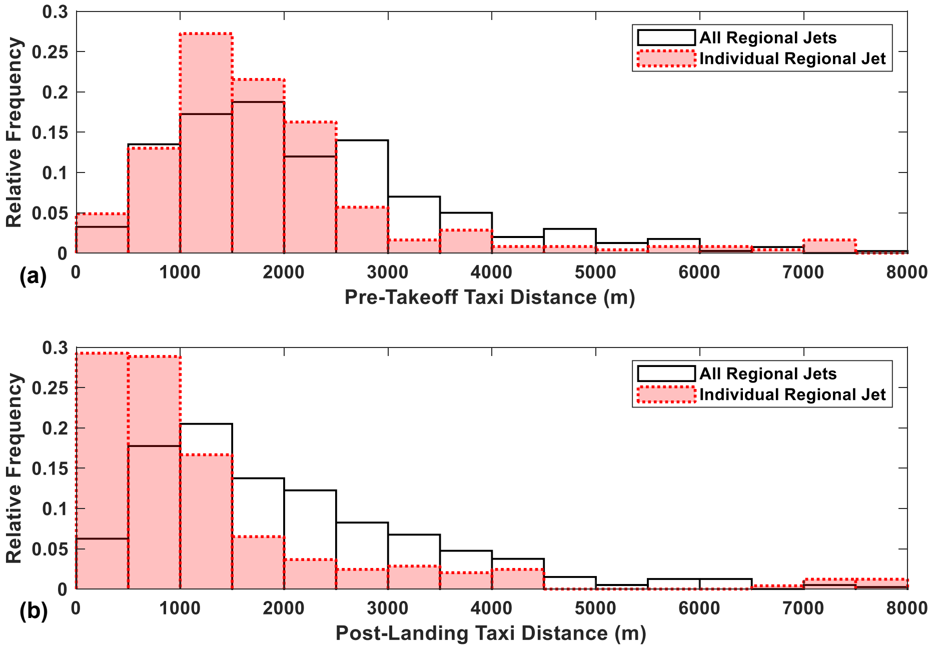

Figure 10: Variation in taxi distances for the overall regional jet fleet and an individual regional jet across (a) pre-takeoff and (b) post-landing taxi phases.

of ground turns as whilst turboprop regional aircraft are observed to perform fewer post-landing turns, they are exposed to an increased occurrence rate of fatigue-critical tight turns when compared to regional jets. On the other hand, it has also been observed that ground turning manoeuvres are less sensitive to the size of regional jet at the overall fleet level, with consistent occurrence rates across both the regional jet (<100 passengers) and large regional jets (100-120 passengers).

Across the regional jet fleets, geographic impacts have been observed within the regional jet and large regional jet fleet concerning the occurrence rate of turns, along with taxi distances, and this is expected to be as a result of the increased size and complexity of North American airports.[16] However, it is important to note that geographic impacts are not observed in fatigue-critical tight turn occurrence rates for regional jet aircraft.

However, when considering individual aircraft within the regional jet fleets, it has been observed that there can be significant differences in tight turn occurrence rates as a direct result of an aircraft's operational base and route network. In addition, prior studies based upon analysis of flight recorder data from individual regional jets would infer that the number of turns performed during a taxi phase lies within the range of five to eight turns per taxi phase.[17,18] Whilst these values are higher than the mode values presented throughout Section 3.1, it is interesting to note that one of the considered aircraft is explicitly stated to be based in North America and the suggested occurrence range inferred from the previous work aligns with the second peak in the turn occurrence histograms for North American regional jets in Figure 5a) and 5b). This could suggest that aircraft employed in the previous studies could also deviate from the occurrence rates and variability observed at the fleet level.

Consequently, the importance of understanding an operator's route network and characteristics when considering the fatigue substantiation of aircraft landing has been reinforced. Therefore, in-keeping with prior work,[4] the results presented within this paper support the growing and continued interested into structural health monitoring for aircraft landing gear across all sizes and categories of civil aircraft.

4.1 Limitations and Future Work

As considered in prior work,[4] the methodology employed to process the ADS-B trajectories does contain limitations, most notably around the robust identification and handling of pushback phases. Therefore, in order to carry out verification of the employed methodology for the regional airliner dataset considered within this paper, 10% of flights across all fleets presented within Table 1 were randomly sampled and the ground manoeuvre sequence manually defined. When comparing the manually identified manoeuvre sequence to that identified by the methodology, it was found that 85% of pre-takeoff taxi phases were correctly characterised, consistent with prior work.[4] In the manually reviewed ADS-B trajectories propagation of errors from the pushback phases were once again identified and future work should

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consider alternative routes to robust pushback identification and segmentation as a priority. In addition, it is important to note that pushback manoeuvres often require tight turns to be performed and consequently, the significant increase in tight turn occurrence rate observed for the individual regional jet in Table 4 may in fact be reduced if pushback turns were accounted for in the rest of the regional jet fleet analysis.

In contrast, only 80% of post-landing phases were fully correct. It was observed that this was typically as a result of sparse ADS-B trajectories in the region of ‘shallow’ turns, such as rapid exit taxiways off runways or other taxiway geometries with limited change in aircraft heading. Sparse ADS-B trajectories in such regions lead to consecutive turns of the same direction merging into a single turn, and future work should aim to explore routes to segregating such merged turns.

As highlighted in Section 2.1, availability of ADS-B ground trajectories is highly dependent on the coverage at given location and as trajectories related to the fleets presented in Table 1 were manually reviewed for completeness prior to being stored, the results presented in Section 3 will be biased towards airports and routes that have adequate ADS-B ground coverage. Future work should explore the various map-matching and filtering approaches presented in the recent literature[1, 10, 12, 22] to support not just an increase in the number of airport geometries that can be considered in a dataset, but also the fidelity of ADS-B position reports throughout complete taxi-phases.

Finally, the sample size presented within this paper is consistent with that employed in prior research concerning ground trajectories of regional turboprops.[15] However, other studies concerning the ground trajectories of narrowbody and widebody aircraft have employed 500-1,000 flights[2, 4] and therefore, future work should also explore the impact of ground manoeuvre statistics on different ground trajectory sample sizes.

5. Conclusion

Aircraft landing gear are exposed to cyclic loading in-service and some of these loads are as a result of ground turns performed during taxiing. To support the growing and continued interest in the adoption of structural health monitoring approaches for aircraft landing gear, air traffic data in the form of Automatic Dependent Surveillance-Broadcast (ADS-B) trajectories has been employed to characterise the ground turning manoeuvres of civil aircraft. Previous studies have focused on narrowbody and widebody aircraft but are yet to consider regional airliners.

A sample of 600 ADS-B trajectories across turboprop, regional jet (<100 passengers) and large regional jet (100-120 passengers) fleets were assembled and processed using a previously-developed methodology to characterise the occurrence rate and variability in pre-takeoff and post-landing taxiway turns. The results presented within this paper have shown that landing gear of regional turboprop aircraft will be exposed to a greater rate of fatigue-critical tight turns than regional jet fleets.

The regional jet and large regional jet fleets were further decomposed into North American and European fleets to explore if geographical impacts on ground turning manoeuvres were present. It was observed that due to European airports typically having smaller and potentially simpler airport geometries, European regional jets typically perform fewer taxiway turning manoeuvres.

Finally, whilst consistency was often observed in fleet-level results, the characterisation of ground turning manoeuvres for an individual regional jet aircraft highlighted that significant differences can exist in the ground manoeuvres performed by a single airframe, as represented by the selected aircraft performing approximately three times the number of tight turns per 10 flights compared to the overall regional jet fleet. Therefore, this paper has further supported the move towards structural health monitoring approaches for landing gear assemblies of regional airliners.

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