



AIRCRAFT LANDING TRAJECTORY CHARACTERISTICS ASSOCIATED WITH RUNWAY OCCUPANCY TIME: AN ADS-B-BASED STUDY

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INFO ARTIKEL	ABSTRACT
Artikel Masuk: 11/09/2026 Artikel Review: 14/09/2026 Artikel Revisi: 25/09/2026	Runway Occupancy Time Landing (ROTL) is an important operational indicator of runway efficiency, as variations in aircraft landing behavior can affect the duration of runway occupancy. This study investigates aircraft landing trajectory characteristics associated with differences in ROTL using Automatic Dependent Surveillance–Broadcast (ADS-B) data. A total of 2,000 Category C landing trajectories recorded between July and October 2025 on Runway 06 and vacating via Taxiway M2 at Soekarno–Hatta International Airport were analyzed. The trajectories were reconstructed at one-second intervals from threshold crossing to runway exit and classified into the 5% lowest and 5% highest ROTL groups. Comparative analysis was conducted using threshold speed and altitude, together with temporal and spatial trajectory profiles represented by altitude–time, speed–time, altitude–horizontal-range, and speed–horizontal-range relationships. The results show a clear difference in threshold speed between the two groups, with mean values of 148.42 kt for the low-ROTL group and 132.07 kt for the high-ROTL group, while mean threshold altitude remained relatively similar at 50.75 ft and 51.43 ft, respectively. The trajectory profiles further indicate differences in the evolution of aircraft speed and altitude from threshold crossing through touchdown and runway rollout. These findings demonstrate that trajectory-level analysis can provide additional insight into aircraft landing behavior associated with variations in runway occupancy time.
Keywords: ADS-B; aircraft landing trajectory; runway occupancy time; landing dynamics; runway efficiency	

Introduction

The continued growth of global air transportation has increased pressure on airport capacity, particularly at major hub airports where runway infrastructure must accommodate high traffic demand within limited operational space. Global forecasts indicate sustained growth in air traffic over the coming decades, with the Asia–Pacific region expected to contribute substantially to this expansion (Airbus, 2025). In Indonesia, this challenge is particularly relevant at Soekarno–Hatta International Airport, which serves as the country’s primary international gateway and handles a high volume of aircraft movements annually (AirNav Indonesia, 2024). Under these conditions, improving the efficiency of existing runway operations is essential for maintaining arrival capacity without relying solely on physical infrastructure expansion.

One important indicator of runway operational efficiency is Runway Occupancy Time Landing (ROTL), generally representing the time required for an arriving aircraft to occupy the runway from threshold crossing until runway vacating. ROTL directly influences the interval during which the runway remains unavailable for subsequent operations and therefore contributes to runway capacity, arrival sequencing, and traffic flow efficiency. Previous studies have identified runway occupancy time as an important component of airport capacity assessment, particularly under high-density traffic conditions (Pavlin et al., 2006; EUROCONTROL,

2023). Consequently, understanding the operational factors associated with ROTL is important for identifying opportunities to improve runway utilization.

Previous approaches to reducing runway occupancy have frequently emphasized airport infrastructure, particularly runway–taxiway configuration and the provision of rapid-exit taxiways. ICAO Doc 9157 and FAA AC 150/5300-13B provide geometric criteria intended to facilitate efficient runway vacating, including appropriate taxiway locations and exit angles (ICAO, 2005; FAA, 2024). Recent studies have similarly demonstrated that runway configuration and rapid-exit taxiway design can influence runway occupancy and capacity (Galagedera & Samarasekara, 2021; Maltinti et al., 2024). However, infrastructure represents only one component of runway occupancy performance. Aircraft operational behavior during the landing process also determines how rapidly an aircraft progresses from threshold crossing to touchdown, ground rollout, and ultimately runway exit.

Landing is a continuous dynamic process involving changes in aircraft altitude, speed, position, and energy state. Conditions observed at the runway threshold therefore represent only the initial state of a sequence that continues through flare, touchdown, deceleration, and runway vacating. Previous research has demonstrated that approach and landing parameters are associated with variations in runway occupancy. Meijers (2019) examined empirical runway occupancy characteristics and highlighted the relevance of aircraft operational parameters, while Lim (2020) investigated the causal effects of landing parameters on runway occupancy time. More recent predictive studies have also identified speed-related variables as important predictors of arrival runway occupancy time (Gao et al., 2023; Nguyen et al., 2022). These findings suggest that aircraft trajectory behavior provides valuable information for understanding differences in ROTL.

The operational relevance of this issue is particularly evident on Runway 06 at Soekarno–Hatta International Airport. Previous studies at the airport reported average ROTL values exceeding the operational benchmark used by AirNav Indonesia, particularly for Category C and D aircraft (Juniawan & Putriekapuja, 2023; Rosmayanti et al., 2024). Runway 06 also operates within a constrained multi-runway environment, making efficient landing operations important for maintaining arrival performance. For aircraft vacating through Taxiway M2, the runway and exit configuration remains constant; therefore, variations in runway occupancy among comparable aircraft operations can provide an appropriate empirical basis for examining differences in landing trajectory behavior.

A previous study using 2,000 ADS-B landing trajectories on Runway 06 demonstrated a clear distinction in threshold conditions between low- and high-ROTL operations. In particular, the 5% lowest ROTL group exhibited a mean threshold speed of 148.42 kt, compared with 132.07 kt for the 5% highest ROTL group, whereas mean threshold altitude remained relatively similar at 50.75 ft and 51.43 ft, respectively. These findings identified threshold speed as an important operational discriminator of runway occupancy performance. However, threshold parameters represent only a single observation point within the overall landing process. Differences observed at threshold crossing may subsequently evolve through the flare, touchdown, and ground-roll phases before the aircraft reaches the runway exit. A trajectory-level examination is therefore necessary to characterize how aircraft states develop spatially and temporally across contrasting ROTL outcomes.

Automatic Dependent Surveillance–Broadcast (ADS-B) data provide an opportunity to conduct such an analysis using observations from actual aircraft operations. ADS-B records contain time-referenced information on aircraft position, altitude, and ground speed, allowing individual landing trajectories to be reconstructed and compared throughout the runway occupancy period. Surveillance-based trajectory data have previously been applied to runway occupancy extraction and analysis (Kumar et al., 2010), while the availability of large operational datasets enables systematic comparison across multiple landing events. Rather than limiting the analysis to aggregate ROTL values or aircraft states at a single location, trajectory reconstruction allows the temporal and spatial evolution of aircraft behavior to be examined from threshold crossing through runway vacating.

Despite increasing research on runway occupancy prediction and landing parameters, the temporal and spatial characteristics distinguishing low- and high-ROTL landing trajectories remain less explicitly characterized. Existing studies commonly evaluate aggregate runway occupancy values, infrastructure characteristics, individual landing parameters, or predictive relationships. Such approaches are valuable for identifying variables associated with ROTL but provide limited explanation of how those differences evolve throughout successive phases of the landing trajectory. In particular, simultaneous comparison of altitude and speed with respect to both elapsed time and horizontal distance can provide a more detailed representation of aircraft behavior during flare, touchdown, and rollout.

Accordingly, this study investigates aircraft landing trajectory characteristics associated with Runway Occupancy Time Landing using empirical ADS-B data from Runway 06–Taxiway M2 at Soekarno–Hatta International Airport. A total of 2,000 Category C landing trajectories recorded between July and October 2025 are analyzed, with particular emphasis on comparing the 5% lowest and 5% highest ROTL groups. The analysis examines threshold characteristics together with altitude–time, speed–time, altitude–horizontal-range, and speed–horizontal-range relationships to characterize differences in the temporal and spatial evolution of landing trajectories.

The scientific contribution of this study lies in extending ROTL analysis from threshold-level and aggregate measurements toward a trajectory-based characterization of landing operations. By comparing contrasting ROTL groups throughout the landing sequence, the study aims to identify how differences in aircraft speed and altitude evolve from threshold crossing through touchdown and rollout. The resulting findings are expected to provide an empirical understanding of landing trajectory characteristics associated with runway occupancy performance and to complement existing approaches based on infrastructure, individual landing parameters, and aggregate ROTL measurements.

Methodology

This study employs a quantitative empirical approach to investigate aircraft landing trajectory characteristics associated with Runway Occupancy Time Landing (ROTL). Historical Automatic Dependent Surveillance–Broadcast (ADS-B) data are used to reconstruct aircraft trajectories from runway threshold crossing to runway vacating. The analysis focuses on comparing landing trajectories associated with contrasting runway occupancy outcomes rather than determining an optimized threshold condition. Accordingly, the methodological framework consists of case-study definition, ADS-B data collection and preprocessing, ROTL-based trajectory classification, and temporal and spatial trajectory analysis.

The study focuses on Category C aircraft landing on Runway 06 and vacating through Taxiway M2 at Soekarno–Hatta International Airport. Maintaining a common runway, aircraft category, and runway exit configuration reduces variability associated with different exit locations and allows the analysis to concentrate on differences in aircraft trajectory behavior. The empirical dataset consists of 2,000 valid landing trajectories recorded between July and October 2025, with Boeing 737-800 and Airbus A320 aircraft representing the predominant aircraft types in the dataset.

The methodological framework of this study is illustrated in Figure 2-1. The analysis begins with the collection of historical ADS-B landing trajectories, followed by data preprocessing and calculation of ROTL for each flight. The processed trajectories are subsequently classified into low- and high-ROTL groups and analyzed using temporal and spatial representations of aircraft altitude and ground speed. The final stage compares the trajectory characteristics of the two groups to identify operational patterns associated with differences in runway occupancy time.

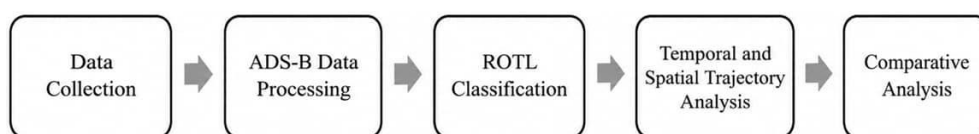


Figure 2-1: Process flow of the research methodology

2.1. Case Study and Data Source

Soekarno–Hatta International Airport was selected as the case-study location because of its high traffic demand and the operational importance of maintaining efficient runway utilization. The analysis is specifically limited to landing operations on Runway 06 with Taxiway M2 as the runway exit. Restricting the observations to a single runway–exit configuration ensures that the compared trajectories are evaluated under a consistent spatial framework and minimizes the influence of different runway exit locations on ROTL.

The spatial configuration of the study area is presented in Figure 2-2. The analysis focuses specifically on landing operations using Runway 06, with Taxiway M2 serving as the common runway exit for all selected trajectories. By maintaining the same runway–exit configuration, the study establishes a consistent spatial reference for comparing aircraft trajectory characteristics and minimizes variability associated with different runway exit locations.

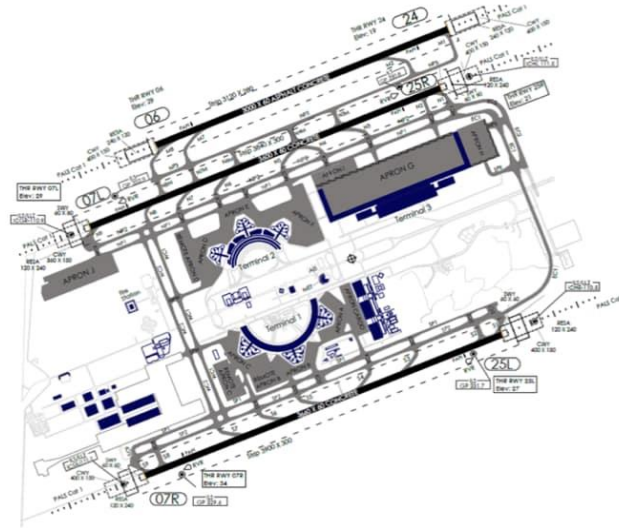


Figure 2-2: Configuration at Soekarno–Hatta International Airport.

As shown in Figure 2-2, the selected operational segment provides a fixed runway–exit configuration for all observations included in the analysis. Consequently, differences in ROTL within the selected sample can be examined under a common spatial framework, allowing greater emphasis to be placed on variations in aircraft landing trajectory characteristics.

Historical aircraft trajectory data were obtained from Flightradar24 (FR24), which provides ADS-B-derived information including aircraft position, altitude, ground speed, and timestamp. The observation period covers July to October 2025. After filtering the recorded arrivals according to runway usage, runway exit, and aircraft category, 2,000 valid Category C landing trajectories were retained for analysis. The dataset primarily consists of Boeing 737-800 and Airbus A320 aircraft.

For each aircraft, the landing trajectory was analyzed from the moment the aircraft crossed the Runway 06 threshold until it fully vacated the runway through Taxiway M2. ROTL was therefore defined as:

$$ROTL_i = t_{exit,i} - t_{THR,i}$$

where $t_{THR,i}$ represents the threshold-crossing time of flight i , and $t_{exit,i}$ represents the time at which the same aircraft vacated the runway through Taxiway M2.

The temporal boundaries used for ROTL measurement are illustrated in Figure 2-3. Threshold crossing is defined as the initial reference point (t_{THR}), while runway vacating through Taxiway M2 represents the end of the runway occupancy interval (t_{exit}). The elapsed time between these two events constitutes the ROTL value assigned to each landing trajectory.

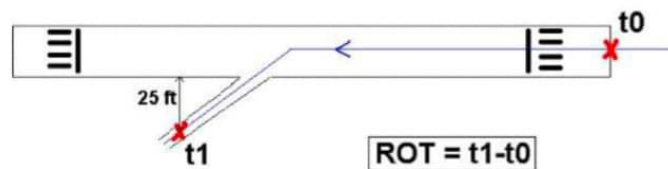


Figure 2-3: Definition of ROTL

This definition was applied consistently to all 2,000 trajectories, ensuring that differences in ROTL represent variations in the elapsed time required for aircraft to progress through the same Runway 06–Taxiway M2 operational segment.

This definition provides a consistent temporal boundary for comparing landing trajectories with different runway occupancy durations.

2.2. ADS-B Trajectory Preprocessing

Raw ADS-B observations contain non-uniform reporting intervals and different numbers of observations among individual flights. Therefore, the trajectory data were processed using Python with the pandas and NumPy libraries to establish a consistent temporal framework across all flights.

Each trajectory was interpolated to a uniform one-second interval. Following interpolation, the trajectory was trimmed so that the first observation corresponded to threshold crossing ($t = 0$) and the final observation corresponded to runway vacating through Taxiway M2. This procedure produced synchronized time-series observations of aircraft altitude, ground speed, and position throughout the runway occupancy period.

For temporal analysis, elapsed time from threshold crossing was calculated as:

$$\Delta t_{i,j} = t_{i,j} - t_{THR,i}$$

where $t_{i,j}$ represents the timestamp of observation j for flight i .

An example of the aircraft trajectory information obtained from FR24 is presented in Figure 2-4. The recorded trajectory provides time-referenced aircraft position together with flight parameters that form the basis for reconstructing individual landing movements. These observations were subsequently processed and standardized into one-second intervals to establish comparable trajectory records across the dataset.

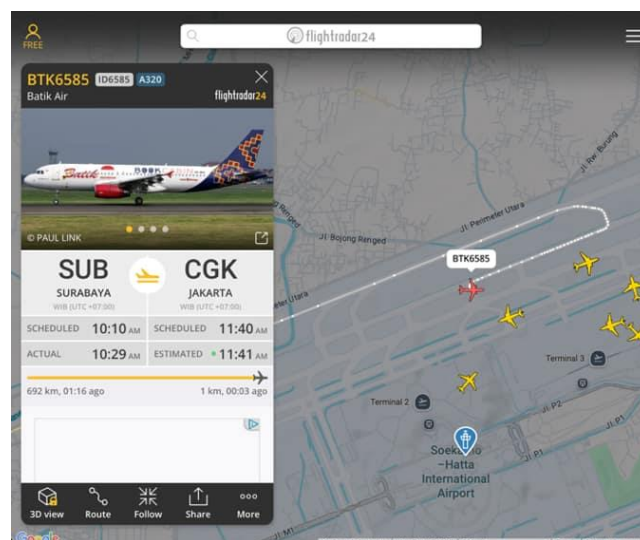


Figure 2-4: Example of landing trajectory from FR24 for Runway 06–M2

The geographical trajectory shown in Figure 2-4 provides an example of the source data used to identify aircraft movement toward Runway 06 and its subsequent progression toward Taxiway M2. Following preprocessing, only the relevant runway occupancy segment from threshold crossing to runway vacating was retained for the subsequent temporal and spatial trajectory analyses.

A spatial reference was also established relative to the Runway 06 threshold. Aircraft geographical coordinates were used to determine horizontal progression along the landing trajectory, allowing speed and altitude to be evaluated not only as functions of elapsed time but also as functions of horizontal range from the runway threshold. Consequently, each processed trajectory contained four principal dimensions for subsequent comparison: elapsed time, horizontal range, altitude, and ground speed.

The use of both temporal and spatial representations is important because two aircraft may reach similar locations on the runway at different times or exhibit different speed profiles at the same runway position. Combining both domains therefore enables a more complete characterization of landing trajectory behavior.

Following preprocessing and trajectory segmentation, a structured dataset was generated for the 2,000 valid landing observations. Each flight record contains the aircraft identifier together with the principal variables required for subsequent ROTL and trajectory analysis. A representative summary of the empirical dataset is provided in Table 2-1.

Table 2-1: Representative sample of the empirical landing dataset..

File	Callsign	Speed (kt)	Altitude (ft)	ROTL (s)
1. IU801.csv	SJV801	128.0	47.63	66
2. IU801.csv	SJV801	129.0	45.66	61
3. IU801.csv	SJV801	133.33	48.14	69
4. JT127.csv	LNI127	145.0	48.65	61
...	...	...	...	...
2000. GA209.csv	GIA209	145.78	58.27	62

As illustrated in Table 2-1, individual landing observations exhibit variations in threshold ground speed, threshold altitude, and ROTL. These differences provide the empirical basis for subsequent trajectory classification. The complete dataset of 2,000 observations was used for ROTL ranking, while the extreme groups were subsequently selected for detailed temporal and spatial trajectory comparison.

2.3. ROTL-Based Trajectory Classification

After ROTL was calculated for all 2,000 flights, the trajectories were ranked according to their individual runway occupancy times. To obtain contrasting operational groups, the 5% lowest and 5% highest ROTL observations were selected.

Each group therefore consisted of 100 landing trajectories:

$$N_{Low} = 100$$

$$N_{High} = 100$$

The low-ROTL group represents the 100 flights with the shortest runway occupancy times in the dataset, whereas the high-ROTL group represents the 100 flights with the longest runway occupancy times.

This extreme-group classification was adopted to provide a clear empirical contrast between landing trajectories associated with short and prolonged runway occupancy. Unlike the previous optimization-oriented analysis, the present study does not use the low-ROTL group to derive an optimal threshold condition. Instead, both groups are treated as observed operational samples and compared throughout the landing trajectory.

The initial comparison considers aircraft states at threshold crossing, particularly ground speed and altitude. Previous analysis of the dataset showed that the low-ROTL group had a mean threshold speed of 148.42 kt, whereas the high-ROTL group had a mean value of 132.07 kt. In contrast, mean threshold altitude differed only slightly, at 50.75 ft and 51.43 ft, respectively. These threshold conditions provide the starting point for examining how the two groups subsequently develop through the landing trajectory.

2.4. Temporal Trajectory Analysis

Temporal trajectory analysis was conducted to examine how aircraft altitude and ground speed evolved as a function of elapsed time after threshold crossing. Two principal relationships were evaluated:

$$h = f(t)$$

and

$$V = f(t)$$

Where h represents aircraft altitude, V represents ground speed, and t represents elapsed time from threshold crossing.

The altitude–time profile was used to characterize the airborne-to-ground transition following threshold crossing. Differences in the temporal development of altitude provide information regarding the progression toward touchdown and the transition from the airborne phase to ground rollout.

The speed–time profile was used to examine the evolution of aircraft ground speed from threshold crossing through touchdown, rollout, and runway vacating. This representation allows differences in speed reduction between low- and high-ROTL operations to be evaluated on a common temporal reference.

For each ROTL group, the individual trajectories were aligned at threshold crossing ($t=0$). Group-level trajectory characteristics were then compared to determine whether systematic differences were observable throughout the landing sequence rather than only at the threshold.

2.5. Spatial Trajectory Analysis

In addition to elapsed time, aircraft trajectory characteristics were evaluated as functions of horizontal range from the runway threshold. The spatial analysis examined:

$$\begin{aligned}h &= f(x) \\ \text{and} \\ V &= f(x)\end{aligned}$$

where x represents horizontal range from the Runway 06 threshold.

The altitude–horizontal-range profile provides a spatial representation of aircraft descent following threshold crossing and allows differences in the airborne-to-ground transition to be examined relative to runway position.

The speed–horizontal-range profile describes how aircraft ground speed changes as the aircraft progresses along the runway. Unlike the speed–time relationship, this representation allows the two ROTL groups to be compared at equivalent runway positions. It is therefore particularly useful for identifying whether differences in runway occupancy are accompanied by distinct spatial patterns of speed evolution during landing and rollout.

The combined temporal and spatial analyses produce four complementary trajectory representations:

1. altitude versus elapsed time;
2. ground speed versus elapsed time;
3. altitude versus horizontal range; and
4. ground speed versus horizontal range.

Together, these profiles are used to characterize differences between the low- and high-ROTL groups throughout the landing sequence.

2.6. Comparative Analysis of Landing Trajectory Characteristics

The final analytical stage integrates the temporal and spatial trajectory profiles to characterize the operational differences associated with ROTL. Rather than relying solely on threshold conditions, the analysis considers the progression of aircraft behavior across the landing sequence:

Threshold crossing → airborne transition/flare → touchdown → ground rollout → runway exit

Comparisons between the low- and high-ROTL groups focus on differences in threshold conditions and subsequent altitude and speed evolution. Where identifiable from the processed ADS-B trajectories, touchdown progression and rollout characteristics are also examined to determine how the initial differences between the groups develop as the aircraft moves toward Taxiway M2.

The interpretation is based primarily on group-level characteristics of the 100 low-ROTL and 100 high-ROTL trajectories. Individual trajectories may be presented as representative examples to illustrate specific patterns; however, they are not treated as the primary evidence for differences between the two groups. This distinction ensures that the conclusions are based on systematic trajectory characteristics rather than on isolated landing events.

Result and Analysis

3.1. ROTL Characteristics of the Observed Landings

The analysis of 2,000 Category C landing trajectories shows substantial variation in Runway Occupancy Time Landing (ROTL) among aircraft operating under the same Runway 06–Taxiway M2 configuration. The observed ROTL values range from approximately 51 to 76 s, indicating that aircraft using the same runway and exit may exhibit considerably different runway occupancy performance.

To examine the trajectory characteristics associated with these differences, the dataset was divided into two contrasting groups consisting of the 5% lowest and 5% highest ROTL observations. Each group contained 100 landing trajectories. This classification provides the basis for comparing aircraft states and their subsequent temporal and spatial evolution throughout the landing sequence.

The comparison is intentionally based on observed low- and high-ROTL operations rather than on predefined optimal or inefficient trajectories. Consequently, the following analysis examines whether differences in runway occupancy are accompanied by systematic differences in aircraft speed and altitude from threshold crossing through touchdown, rollout, and runway vacating.

Table 3-1: Threshold characteristics of low- and high-ROTL groups

Parameter	5% Lowest ROTL	5% Highest ROTL	Difference
Number of Trajectories	100	100	-
Mean threshold speed (kt)	148.42	132.07	16.35
Mean threshold altitude (ft)	50.75	51.43	-0.68

As summarized in Table 3-1, the principal difference between the two ROTL groups is observed in threshold ground speed. The low-ROTL group crossed the threshold at a mean ground speed of 148.42 kt, which is 16.35 kt higher than the 132.07 kt recorded for the high-ROTL group. In comparison, the difference in mean threshold altitude is only 0.68 ft. The substantially larger separation in speed than in altitude suggests that the two groups enter the analyzed landing sequence with markedly different longitudinal states while maintaining broadly comparable vertical conditions. These initial differences establish the reference conditions for the subsequent temporal and spatial trajectory comparisons.

These results indicate that the two groups begin the runway occupancy period at substantially different speed states despite having relatively similar threshold altitudes. However, threshold conditions alone do not describe how these differences develop throughout the remaining landing sequence. The temporal and spatial trajectory profiles are therefore examined in the following sections.

3.2 Temporal Characteristics of Landing Trajectories

3.2.1 Altitude–Time Characteristics

The altitude–time profiles were aligned at threshold crossing, defined as ($t=0$), to compare the vertical development of low- and high-ROTL trajectories using a common temporal reference. At threshold crossing, the two groups exhibit similar mean altitudes, with values of 50.75 ft for the low-ROTL group and 51.43 ft for the high-ROTL group.

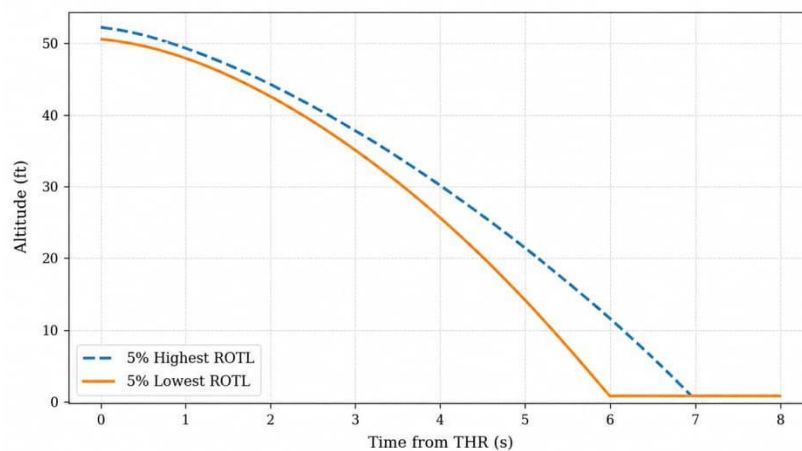


Figure 3-1: Relationship between Altitude and ROTL

Figure 3-1. Altitude–time profiles of the 5% lowest and 5% highest ROTL groups.

Figure 3-1 shows that both groups begin the analyzed trajectory at comparable threshold altitudes of approximately 51 ft, consistent with the values reported in Table 3-1. However, the subsequent altitude profiles diverge during the airborne-to-ground transition. The low-ROTL profile reaches ground level at approximately 6 s after threshold crossing, whereas the high-ROTL profile reaches ground level at approximately 7 s. This approximately one-second difference indicates a shorter airborne transition after threshold crossing for the low-ROTL group.

Although the difference is relatively small in absolute duration, it occurs during the initial phase of runway occupancy and therefore contributes to the temporal separation between the two groups before ground rollout begins. The result also demonstrates why threshold altitude alone provides limited explanatory information: despite nearly identical initial altitudes, the subsequent vertical trajectories do not evolve identically.

The small difference in initial altitude indicates that both groups enter the runway environment from a broadly comparable vertical position. Therefore, the substantial difference in ROTL cannot be explained simply by a large difference in threshold altitude.

Following threshold crossing, the altitude–time profiles provide a means of examining the transition from the airborne phase toward touchdown. Any separation between the two profiles during this interval reflects differences in how the vertical trajectory develops after the aircraft crosses the threshold. In contrast to a threshold-only comparison, the temporal representation allows the progression of the landing transition to be evaluated continuously rather than from a single observation point.

3.2.2 Speed–Time Characteristics

A substantially clearer contrast between the two ROTL groups is observed in their initial speed conditions. At threshold crossing, the low-ROTL group has a mean ground speed of 148.42 kt, compared with 132.07 kt for the high-ROTL group.

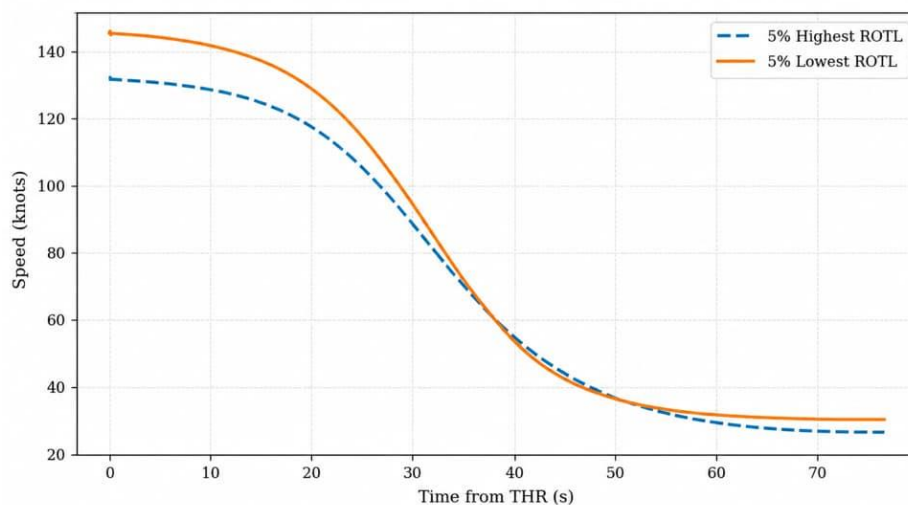


Figure 3-2: Relationship between Speed and ROTL

Figure 3-2. Ground speed–time profiles of the 5% lowest and 5% highest ROTL groups.

Figure 3-2 demonstrates that the difference between the two groups is not restricted to the instant of threshold crossing. The low-ROTL group begins at a substantially higher mean ground speed and retains a higher speed during the initial landing transition. As elapsed time increases, both profiles progressively decrease and move toward similar low-speed conditions during the later rollout phase. The separation between the profiles therefore becomes smaller as the aircraft approach runway-exit conditions.

An important observation from this profile is that a higher threshold speed is not directly equivalent to a longer runway occupancy time in the observed dataset. The low-ROTL group entered the runway occupancy interval at a higher ground speed but completed the Runway 06–M2 segment in less time. This indicates that

threshold speed should not be interpreted independently from the subsequent evolution of aircraft speed during landing and rollout. Instead, the complete speed trajectory determines how the initial speed state develops toward runway-vacating conditions.

The 16.35 kt difference at ($t=0$) demonstrates that the two groups begin the measured runway occupancy period with distinctly different speed states. The speed–time profiles subsequently allow these initial differences to be traced throughout touchdown and ground rollout.

This temporal representation is particularly important because ROTL is itself a time-based measure. Therefore, differences in the rate and timing of speed evolution can directly influence when an aircraft reaches the conditions required to vacate the runway through Taxiway M2. Rather than interpreting threshold speed independently, the trajectory-based approach considers how the initial speed state develops over the complete runway occupancy period.

The comparison therefore extends the threshold-level finding by examining whether the separation in aircraft speed persists, decreases, or changes during the landing and rollout phases.

3.3 Spatial Characteristics of Landing Trajectories

Temporal trajectory profiles describe how aircraft states evolve with elapsed time, but they do not directly indicate where these changes occur along the runway. Therefore, altitude and ground speed were additionally evaluated with respect to horizontal range from the Runway 06 threshold.

3.3.1 Altitude–Horizontal-Range Characteristics

The altitude–horizontal-range relationship represents the vertical trajectory as a function of aircraft progression from the runway threshold.

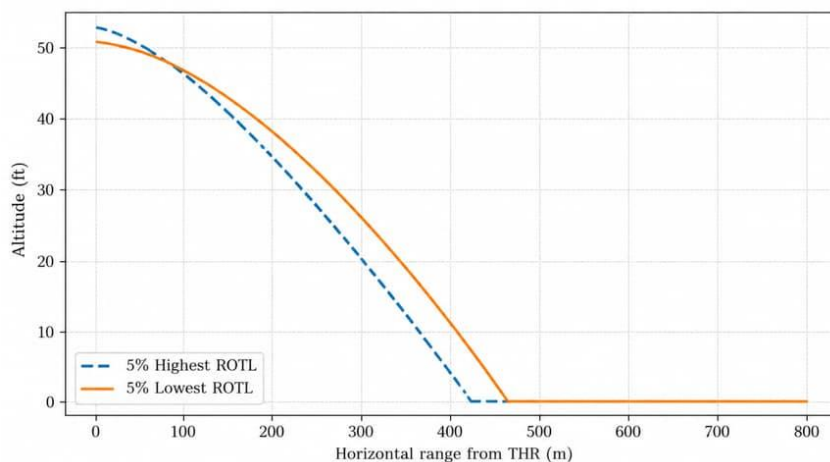


Figure 3-3. Altitude–horizontal-range profiles of the 5% lowest and 5% highest ROTL groups.

Figure 3-3 compares the vertical trajectories of the low- and high-ROTL groups as a function of horizontal range from the runway threshold. In contrast to the altitude–time representation, this spatial profile allows the vertical state of the aircraft to be evaluated at comparable runway-relative positions. The spatial separation observed during the airborne-to-ground transition therefore indicates that similar threshold altitudes may develop into different vertical trajectories after threshold crossing.

Because the two groups have similar threshold altitudes, the spatial comparison is particularly useful for examining whether their subsequent descent toward the runway surface develops differently after threshold crossing. The location at which altitude approaches the runway surface can also provide information regarding touchdown progression relative to the threshold.

This representation complements the altitude–time analysis. An altitude difference at a particular elapsed time does not necessarily indicate a different vertical geometry because aircraft may progress along the runway at different speeds. By expressing altitude as a function of horizontal range, the vertical behavior of the two groups can instead be compared at approximately equivalent runway positions.

3.3.2 Speed–Horizontal-Range Characteristics

The speed–horizontal-range relationship provides a spatial representation of aircraft speed management during the landing and rollout phases.

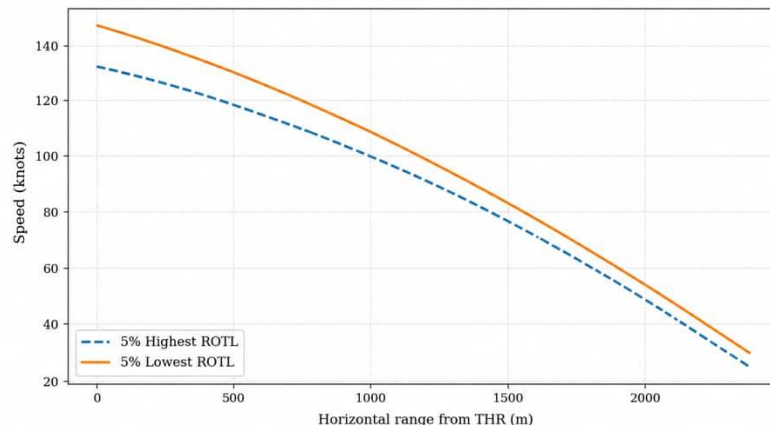


Figure 3-4. Ground speed–horizontal-range profiles of the 5% lowest and 5% highest ROTL groups.

Figure 3-4 presents the corresponding ground-speed profiles as a function of horizontal range. The comparison demonstrates how the initial 16.35 kt difference in threshold speed develops as the aircraft progress toward Taxiway M2. This spatial representation complements the speed–time analysis by showing whether differences in speed are maintained at equivalent positions along the runway rather than merely at equivalent elapsed times.

Unlike the speed–time representation, this analysis compares aircraft speed at equivalent positions relative to the runway threshold. It therefore provides additional information on how the available runway distance is utilized during deceleration and progression toward Taxiway M2.

The low- and high-ROTL groups enter this spatial profile with substantially different threshold speeds. The subsequent development of the profiles can be used to determine whether this speed difference persists along the runway and where the trajectories begin to converge as the aircraft approach runway-exit conditions.

The combination of speed–time and speed–horizontal-range profiles is particularly useful because an aircraft may reduce speed rapidly in time while still exhibiting a different spatial deceleration pattern. Evaluating both representations therefore provides a more complete description of rollout behavior associated with different ROTL outcomes.

3.4 Integrated Analysis of Landing Trajectory Characteristics

The combined results demonstrate that ROTL should be examined as the outcome of a sequence of aircraft states rather than solely as an aggregate time value. The two groups begin the measured landing sequence with nearly identical mean threshold altitudes but substantially different mean threshold speeds. The low-ROTL group crosses the threshold at 148.42 kt compared with 132.07 kt for the high-ROTL group, while the corresponding altitude values differ by less than 1 ft.

This contrast establishes an important initial condition for the subsequent trajectory analysis. However, the principal contribution of the present study is not merely the identification of this threshold-speed difference, because threshold characteristics have already been examined in previous work. Instead, the temporal and spatial profiles provide a framework for tracing how differences observed at threshold crossing evolve through the airborne-to-ground transition and subsequent runway rollout.

The four trajectory representations provide complementary information. Altitude–time describes the temporal development toward touchdown, whereas altitude–horizontal-range places this vertical transition within the spatial runway reference. Similarly, speed–time describes the temporal development of aircraft speed during runway occupancy, while speed–horizontal-range indicates how speed changes relative to runway position. Their combined interpretation therefore connects the initial aircraft state at threshold crossing with subsequent landing behavior and the resulting runway occupancy duration.

From an operational perspective, this trajectory-based representation is useful because two landings with different ROTL values may not differ at only one point in the landing process. Instead, the observed runway

occupancy outcome may reflect differences that develop across successive phases of the trajectory. Consequently, evaluating aircraft behavior throughout the landing sequence provides a more detailed characterization of low- and high-ROTL operations than threshold parameters or aggregate ROTL values considered independently.

The findings therefore support the use of ADS-B trajectory analysis as an empirical approach for examining runway occupancy performance. By reconstructing aircraft behavior in both temporal and spatial domains, differences between low- and high-ROTL operations can be evaluated throughout the complete runway occupancy period, providing additional operational insight into the trajectory characteristics associated with ROTL.

Conclusions

This study investigated aircraft landing trajectory characteristics associated with Runway Occupancy Time Landing (ROTL) using 2,000 ADS-B-derived trajectories of Category C aircraft operating on Runway 06 and vacating via Taxiway M2 at Soekarno–Hatta International Airport. The analysis compared the 5% lowest and 5% highest ROTL groups through temporal and spatial representations of aircraft altitude and ground speed from threshold crossing to runway exit.

The results show that the most apparent difference between the two groups is observed in aircraft ground speed at threshold crossing. The low-ROTL group recorded a mean threshold speed of 148.42 kt, compared with 132.07 kt for the high-ROTL group, representing a difference of 16.35 kt. In contrast, mean threshold altitude was relatively similar between the groups, at 50.75 ft and 51.43 ft, respectively. These findings indicate that contrasting ROTL outcomes are associated with substantially different initial speed characteristics despite comparable altitude conditions at the runway threshold.

Beyond threshold-level comparison, the temporal and spatial trajectory framework enables aircraft behavior to be examined throughout the landing sequence. The combined altitude–time, speed–time, altitude–horizontal–range, and speed–horizontal–range representations provide complementary perspectives for characterizing how differences between low- and high-ROTL operations evolve from threshold crossing through the airborne-to-ground transition and runway rollout. Therefore, ROTL can be evaluated not only as an aggregate occupancy duration but also in relation to the evolution of aircraft states throughout the landing trajectory.

The findings demonstrate the potential of ADS-B trajectory analysis for providing a more detailed empirical characterization of runway occupancy performance. For the Runway 06–Taxiway M2 case, the results emphasize the relevance of aircraft speed characteristics in distinguishing low- and high-ROTL operations, while threshold altitude shows considerably less variation between the two groups. Future studies may extend this trajectory-based approach by incorporating additional operational factors, such as aircraft type, meteorological conditions, runway surface conditions, traffic interactions, and pilot-dependent landing behavior, to further explain variations in runway occupancy time.

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