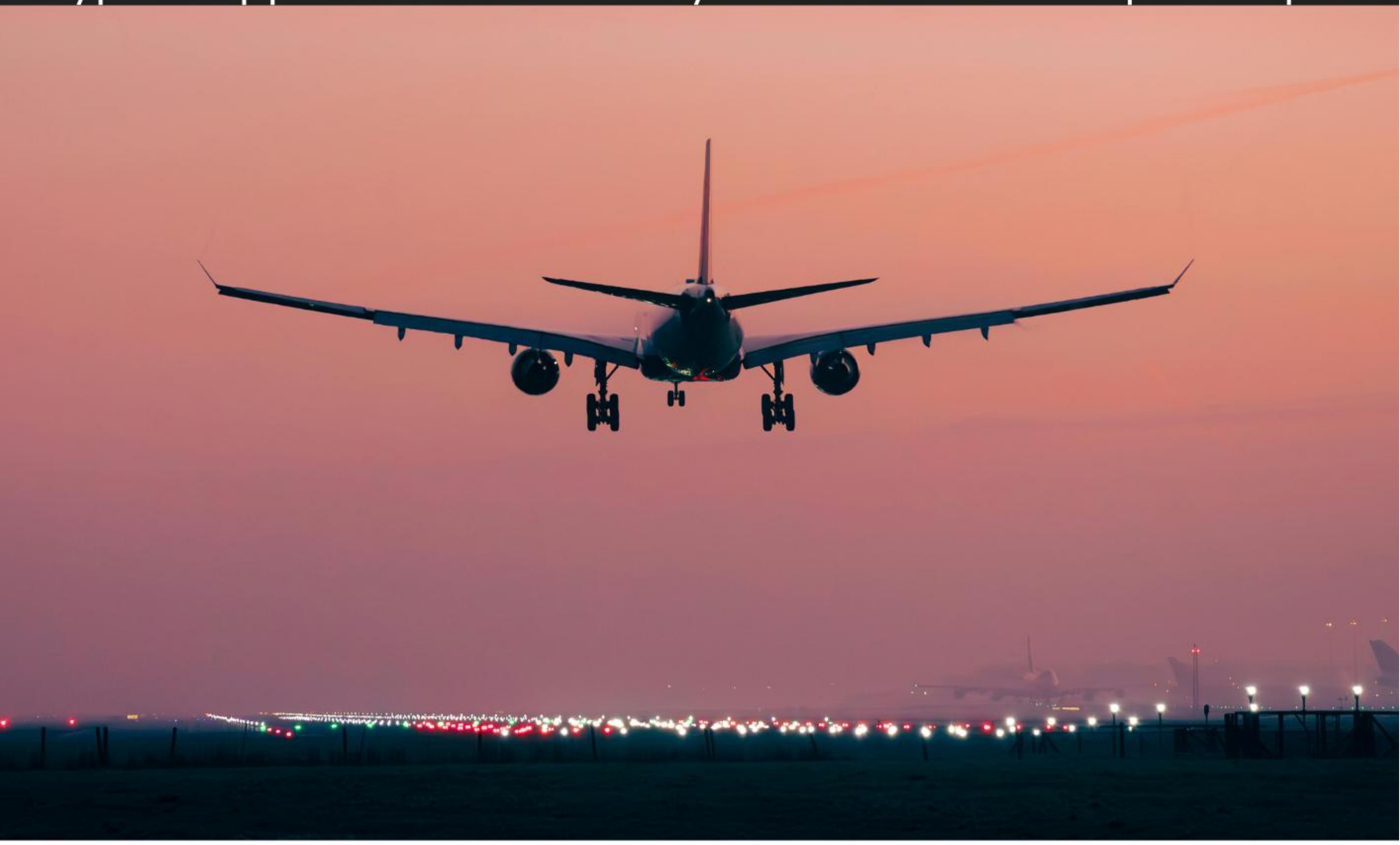
Atypical Approaches

Correlating Route Design and Operational Practices with Atypical Approaches on Runway 18C and 18R at Schiphol Airport



THESIS

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Thesis

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Use of generative AI Disclaimer

Throughout this thesis, generative AI tools were incorporated in several supportive roles:

- **Writing support:** AI was consulted to refine certain passages, helping to improve clarity, flow, and overall readability.
- **Code optimisation:** AI was used to review selected Python code fragments and propose more efficient alternatives, particularly for handling large datasets.
- **Debugging assistance:** When parts of the Python code produced errors or unexpected behaviour, AI was used to analyse the problematic sections and offer possible explanations. These insights contributed to identifying and resolving the underlying issues.

The AI source that has been used includes:

- ChatGPT version 5.2

Abstract

Atypical approaches are characterised by late, sharp energy corrections close to the runway that remain operationally relevant at Amsterdam Airport Schiphol (EHAM) and are not yet fully explained by published procedure design or routine operational variability. This thesis investigates whether atypical energy-loss events after the Final Approach Fix (FAF) and stability-related exceedances at the FAF on runways 18R and 18C are associated with published arrival procedure characteristics and with upstream vertical states, as observed in operational trajectory data.

First, the published night-transition arrival routes from ARTIP, RIVER, and SUGOL were evaluated against ICAO PANS-OPS vertical design criteria to establish a formal baseline. Second, surveillance trajectories from LVNL's VEMMIS database were reconstructed and reduced to a single FAF-representative observation per flight, including airspeed, vertical speed, bank angle, and ILS dot-equivalent deviations. Atypical behaviour during daytime operations was classified using an energy-management proxy: approaches were labelled atypical when airspeed reduction between the FAF (≈6.2 NM) and 3 NM exceeded 20 kt per NM.

Results show that the published night transitions are compliant by design and that night-time operations exhibit no systematic instability patterns at the FAF; parameter exceedances occur in isolation and do not combine into atypical states. In daytime operations, atypical outcomes are runway-dependent. While FAF altitude distributions are broadly similar across runways, runway 18R shows a strong dependence of post-FAF atypical energy dissipation on FAF vertical state, whereas runway 18C exhibits a weaker FAF-state effect and a clearer role of upstream persistence closer to the FAF (e.g., near SIDNI). Overall, the findings indicate that procedure compliance alone does not explain atypical behaviour; instead, atypical outcomes are best interpreted as arising from the interaction between arrival geometry, the evolution and persistence of vertical energy toward the FAF, and the remaining distance available for stabilisation.

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Abbreviations

Definitions	Meaning
AGL	Above Ground Level
ATC	Air Traffic Control
eAIP	electronic Aeronautical Information Publication
EHAM	Schiphol Amsterdam Airport
FAF	Final Approach Fix
FL	Flight Level
IAF	Initial Approach Fix
IAP	Instrument Approach Procedure
IAS	Indicated Speed
ICAO	International Civil Aviation Organisation
IF	Intermediate Fix
LVNL	Luchtverkeersleiding Nederland
MOC	Minimum Obstacle Clearance
NM	NM
NSA	Non-Stabilised Approach
NSC	Non-Compliant Approach
NTZ	No-Transgression Zone
OLS	Obstacle Limitation Zone
STAR	Standard Terminal Arrival Route
TEM	Threat and Error Management

1. Introduction

Amsterdam Airport Schiphol EHAM is one of Europe's busiest hubs. At peak times, more than 100 aircraft land and take off every hour (LVNL, 2025). To keep this volume safe and efficient, arrivals are organised well before the runway. Aircraft are sequenced onto approach routes, given speed guidance to maintain separation, and positioned so that each flight can turn onto the runway heading at a prescribed height and distance. These structured arrival and approach procedures support predictable flows, helping to manage the workload for pilots and air traffic controllers.

Within this structure, the approach is the final part of a flight, where the aircraft lines up with the runway and descends to the touchdown point. In normal operations, the aircraft follows a path published in the Aeronautical Information Publication (AIP), which sets out the intended track and vertical profile. To support predictable flows, aircraft are expected to maintain prescribed speeds, altitudes and the 3° glide path towards the runway.

A crucial aspect of this structure is the Final Approach Fix (FAF). This point marks the beginning of the final approach segment, where the aircraft intercepts the glide path and begins its continuous descent toward the runway. It defines the transition from the approach phase to the final approach. After the FAF, the aircraft should be configured for landing and continue on a stabilised approach all the way to touchdown. A stabilised approach means the aircraft stays on the intended approach path, flies at the planned approach speed for its weight, and remains in the planned landing configuration. Power should be steady, and the rate of descent should be consistent with the planned path.

Pilots monitor a stabilised approach using the cockpit displays that show how far the aircraft is from the centre of the path. Small markers called *dots* indicate deviation. Staying within one dot to the side and one dot above or below the glide path indicates the aircraft is well within acceptable limits. The target approach speed is the operator's reference speed for the current weight, often called *Vref*. In practice, the speed should be close to that target, typically from five knots below to ten knots above (Pilot Institute, 2025).

When the aircraft is configured early within the approach, and the above-mentioned conditions are met, only routine inputs are needed. These are the small, continuous adjustments to pitch, power, and trim that keep the aircraft on the glide path and at the correct speed without large corrections. This keeps the approach stable, predictable, and ready for a safe landing.

To better understand when and how approaches deviate from this stable condition, previous research has examined aircraft energy management during the final miles of flight. (van Renssen, 2025) combines height and speed into a single view of total specific energy during the last miles of flight based on the energy-based framework by Jarry, Delahaye, & Nicol, (2018). van Renssen, (2025) focused on the segment from the FAF, about 6.2 NMs from the runway, to 3 NMs, where standard procedures expect a smooth descent on a 3° path with steady deceleration. Using this energy view, an approach is considered atypical when the cumulative energy that is being lost in this segment implies a deceleration above a practical upper reference of 20 knots per NM.

van Renssen (2025) implemented an energy-based framework to detect atypical approaches at Schiphol. This framework, combining aircraft height and speed into a single energy measure, was applied to three years of surveillance data to evaluate operational approaches at EHAM. The results showed that approximately 20.2 in 1,000 landings met the atypical criteria. Such approaches occurred about 2.5 times more often in flights that ended in a go-around and accounted for roughly 5% of all go-arounds. Atypical patterns were also observed in approaches that continued to land, underlining their operational relevance. Variation between runways and inbound flows, such as higher rates on runway 18C and via ARTIP, suggests that contextual factors and route design may play a role.

These observations reveal a practical gap in understanding. Atypical approaches occur, but the reasons they develop at or beyond the FAF are not yet fully understood. This thesis, therefore, examines plausible, potentially interacting explanations. First, a procedure-design perspective is considered: the published routing and constraints upstream of the FAF may not consistently provide sufficient distance, time, or predictability for arriving aircraft to stabilise on the intended lateral path and target speed under operational conditions. Second, an operational-data perspective is considered by analysing recorded surveillance trajectories to characterise how aircraft actually fly the procedure in practice, and to identify where and how deviations from the intended vertical and speed profiles emerge as the approach progresses toward and beyond the FAF. Because the FAF is where the designed final approach should begin in a stable, fully configured state, it serves as a useful reference for examining the gap between procedure and practice. Using the FAF as a reference point, this thesis determines whether routine operational conditions or the published route design before the FAF indirectly contribute to atypical approaches at EHAM on runways 18R and 18C.

1.1 Problem Statement

At EHAM, it remains unclear whether approach route design and/or routine operational conditions for runways 18R and 18C lead to atypical aircraft states at the FAF. In particular, the published flight paths starting from the initial waypoints, SUGOL, ARTIP and RIVER to the FAF might not always provide enough time, distance, or predictability for aircraft to stabilise on the intended path and speed in real conditions. A design that works in light traffic might become a critical during busy periods or when a runway change takes place. As a result, some approaches may arrive at the FAF without a stable set-up, increasing the likelihood of atypical conditions at that point.

1.2 Thesis Main Objective

The main objective of this thesis is to determine whether variations in how aircraft follow the intended arrival path between the IAF, waypoints ARTIP, RIVER, and SUGOL, and the FAF are related to atypical states, by comparing the published approach procedures and assessing how procedural design characteristics, might impose atypical conditions at the FAF.

1.3 Thesis Sub-Objectives

From the main objective, the following sub-objectives have been established:

I. To define the formal design characteristics of the currently published night-transition arrival routes to runways 18C and 18R at EHAM, including altitude, speed, and lateral path constraints from the initial approach fixes (IAFs) to the FAF. This sub-objective aims to assess whether the currently published night-transition procedures are compliant with applicable ICAO PANS-OPS design criteria.

II. To determine whether atypical approach behaviour occurs during night-time operations by analysing aircraft state at the FAF, using vertical speed, airspeed, bank angle, and ILS deviation as indicators of approach stability to runways 18C and 18R.

III. To identify and quantify the occurrence of atypical approach behaviour during daytime operations at runways 18C and 18R, and to evaluate the relationship between vertical state at the FAF and subsequent atypical energy-loss behaviour during the final approach segment.

IV. To assess whether atypical daytime approach behaviour is imposed upstream of the FAF by analysing aircraft vertical state at key upstream reference points, and to determine whether persistence of elevated or lowered vertical energy closer to the FAF increases the likelihood of atypical energy-loss behaviour between the FAF and 3.0 NM from the runway threshold.

1.4 Research Questions

The main question for this thesis will be:

"To what extent are atypical energy-loss events after the FAF (between the FAF and 3 NM) and stability-related exceedances at the FAF for runways 18R and 18C at Amsterdam Airport Schiphol associated with published arrival procedure design characteristics and upstream vertical states, as observed in operational trajectory data?"

1.5 Scope and Limits

This thesis examines approach trajectories at EHAM from the three IAFs: ARTIP, RIVER, and SUGOL to runways 18C and 18R. The analysis focuses on instrument arrival procedures associated with these runways, as illustrated in Figure 1, where the area of interest is indicated by the dotted lines in the mentioned figure. The primary focus lies on the arrival segments from the IAFs through the Intermediate Approach Segment and across FAF, extending further into the early Final Approach Segment up to 3.0 NM from the runway threshold.

This thesis evaluates the published arrival route design and its relationship with observed aircraft behaviour, with particular attention to vertical and energy-related characteristics as aircraft transition from the en-route environment to the final approach. In line with the findings of van Renssen (2025), which highlighted energy-management challenges close to the runway, this thesis investigates whether the published arrival procedures to runways 18C and 18R are associated with atypical approach states either at or downstream of the FAF.

The scope of the analysis is therefore limited to the portion of the arrival between the initial approach fixes and the early final approach segment, where stabilisation is expected to occur.

This thesis is limited to:

- Approaches to selected runways at Schiphol: Runways 18C and 18R only. Operations involving parallel runway configurations or interactions with other runways are not considered.
- Instrument approach procedures (IAPs): Visual approaches are excluded from the analysis.
- Published procedural constraints:
    - The FAF crossing altitudes are fixed at 2,000 ft for runway 18R and 3,000 ft for runway 18C and are treated as immutable procedural constraints.
    - The initial approach fixes ARTIP, RIVER, and SUGOL have fixed minimum crossing altitudes, which are not subject to modification within this thesis.
- Vertical and energy-related aircraft states: The analysis focuses on altitude, airspeed, vertical speed, and derived energy-loss metrics. Lateral deviations are evaluated only insofar as they relate to ILS tracking performance near the FAF.

- Observed trajectory data only: This thesis analyses radar-derived aircraft trajectories and does not evaluate air traffic control instructions, tactical sequencing decisions, or flight crew intent. Any operational behaviour is therefore interpreted as an observed outcome rather than as the result of specific ATC or pilot actions.
- Single-runway operations: Although runways 18C and 18R are analysed separately, interactions arising from simultaneous parallel runway operations are excluded.
- The influence of meteorological conditions is excluded from the scope of this thesis. While weather can affect aircraft energy management, its variability and indirect relationship to published procedure design place it outside the analytical focus of this thesis.

This thesis does not aim to redesign EHAM arrival procedures or propose operational changes. Instead, it seeks to improve the understanding of how published procedure design characteristics relate to observed approach behaviour, particularly with respect to atypical energy states at the FAF and in the early final approach.

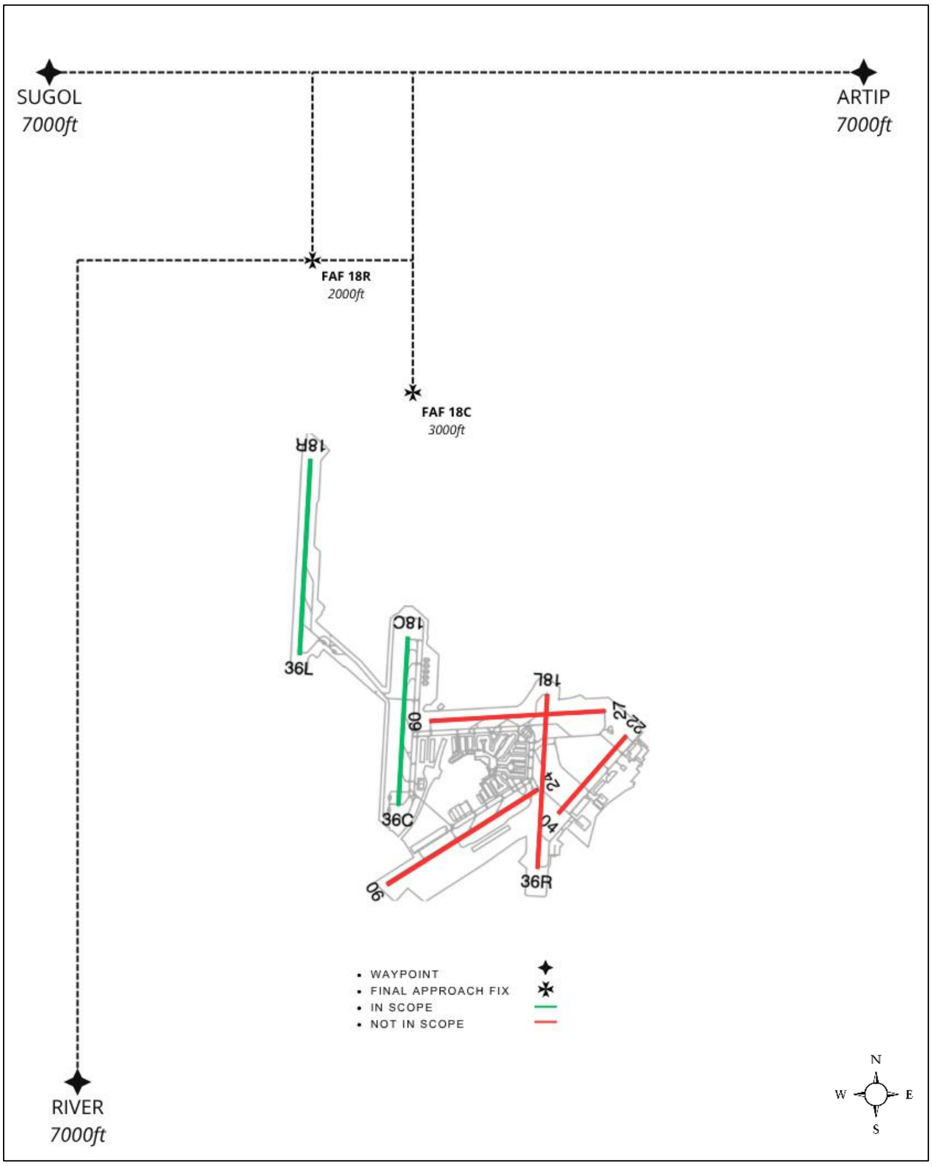


Figure 1 Scope of the thesis visualised (Not to scale)

1.6 Thesis Structure

This thesis is structured to progressively link published arrival procedure design to observed approach behaviour using trajectory-based analysis.

Chapter 2 presents the theoretical framework underpinning the research. It introduces key concepts related to instrument approach design, approach stability, and aircraft energy management, and reviews relevant literature on atypical and unstable approaches. The chapter also outlines the applicable ICAO PANS-OPS design criteria that form the procedural reference for the analysis.

Chapter 3 describes the methodological approach adopted within this thesis. It details the data sources, preprocessing steps, and analytical techniques used to evaluate both night-time and daytime approach behaviour, including the definition of atypical approach states and the derivation of upstream vertical-state metrics.

Chapter 4 presents and discusses the results of the analysis. The chapter first establishes the procedural design baseline by assessing the compliance of the published night-transition arrival routes with ICAO PANS-OPS criteria. It then evaluates observed approach behaviour during night-time operations, followed by an extensive analysis of daytime arrivals to identify atypical approach states and examine the influence of upstream vertical conditions on downstream energy management.

Chapter 5 synthesises the findings of the results chapter and draws conclusions in relation to the research objectives and the main research question. It reflects on the implications of the results for understanding approach stability at EHAM and highlights limitations of this thesis.

Chapter 6 concludes the thesis by presenting recommendations for future research and potential applications of the analytical approach developed in this thesis.

2. Theoretical Framework

At major airports such as EHAM, arriving aircraft are expected to follow published descent and speed profiles from the IAF until they reach a stable configuration at the FAF. When an aircraft does not meet these requirements at the FAF, the approach is considered atypical. Atypical is considered when involved flying faster or at altitudes higher than prescribed, intercepting the glide path from above, or descending at an excessive rate. These deviations are operationally significant because they might reduce stability and increase the likelihood of a go-around, which is when a landing is discontinued and the aircraft climbs to attempt another approach.

A previous study by van Renssen (2025) analysed these approaches at EHAM, specifically for runways 18R and 18C, using the total energy concept introduced by Jarry, Delahaye and Nicol (2018). This concept combines an aircraft's height and speed into a single measure of energy. In a normal approach, this energy should decrease gradually and predictably as the aircraft descends. When the energy level decreases too slowly or irregularly, the aircraft may enter an atypical state, indicating that the approach is not stabilised.

Building on this, van Renssen (2025) applied the energy framework to three years of surveillance data at EHAM. The analysis distinguished between non-stabilised approaches, where limits on speed, bank angle or descent rate were exceeded, and non-compliant approaches, where published requirements such as the target speed or altitude at the FAF were not met. The results showed that a measurable number of aircraft reached the FAF in atypical conditions, suggesting that certain elements of the arrival structure or traffic management may influence these outcomes.

Instrument Approach Procedures and ICAO *Doc 8168*

The design of instrument arrival and approach procedures is established in the International Civil Aviation Organization (ICAO) document: ICAO *Doc 8168 - Procedures for Air Navigation Services: Aircraft Operations* (PANS-OPS). This documents provides the design and operational framework for Standard Terminal Arrival Routes (STARs) and Instrument Approach Procedures (IAPs) used at airports. STARs define the published routing for arriving aircraft from the en-route structure to the terminal area, while IAPs define the published procedure from the terminal area to the runway for landing.

According to ICAO *Doc 8168*, Volume I – Flight Procedures, the IAP consists of a series of predetermined manoeuvres that guide an aircraft safely from the en-route (cruise flight) structure to a position for which a landing can be completed, or, if necessary, a missed approach can be executed.

The procedure is divided into four segments;

- Initial Approach
- Intermediate Approach
- Final Approach
- Missed Approach

Figure 2 illustrates the structure of a standard instrument approach procedure, which guides aircraft from the arrival route to the runway. The procedure begins at the IAF, which at EHAM can be one of three entry points: SUGOL, ARTIP or RIVER. It consists of three main parts, known as the **initial**, **intermediate** and **final** approach segments.

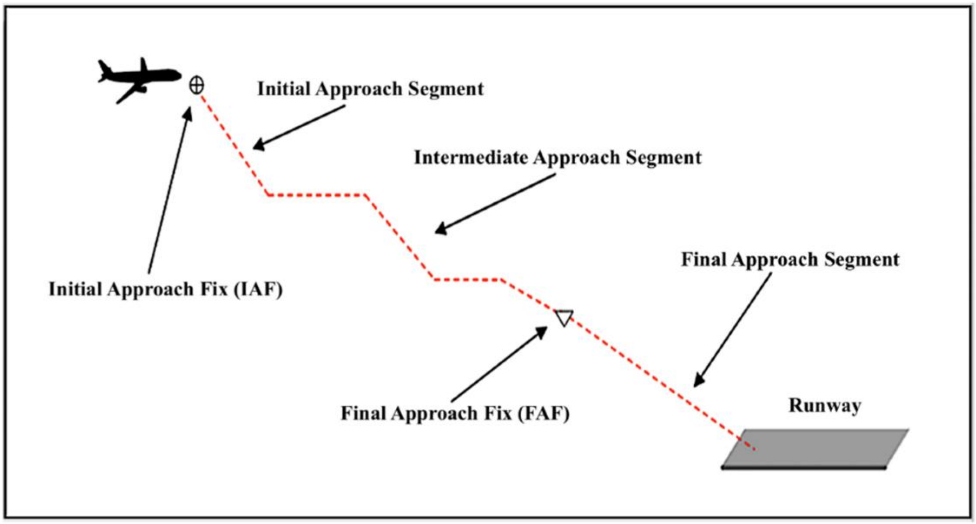


Figure 2 Approach Segment (Alharbi, Abdel-Malek, John Milne, & Wali, 2022)

The **initial** approach segments align the aircraft with the approach path and enable a controlled descent from the en-route altitude to an intermediate level, where the **intermediate** approach segments provide a stable configuration and allow deceleration and final descent preparation. After leaving the **intermediate** approach, the **final** approach segment establishes the aircraft on a defined vertical and lateral path towards the runway, normally using a nominal descent angle of 3° (5.2%).

The **final** approach segment begins at the FAF, where the aircraft intercepts the glide path and continues descending towards the runway for landing. In a precision approach, this usually occurs at an altitude between 1,000 to 3,000 feet above the runway, corresponding to about 3 to 10 NM from the beginning of the runway, depending on the angle of descent. From this point onward, the aircraft should remain stable on the glide path until touchdown.

The FAF itself is an important part of the approach design. It marks the point where an aircraft leaves the **intermediate** segment and begins the final approach. By the time an aircraft passes the FAF, it should already be configured for landing and within published altitude and speed limits. In principle, this ensures a predictable, stabilised descent. In practice, however, trajectories at and beyond the FAF often diverge from the intended path. For this reason, the FAF provides a useful reference for evaluating whether published procedures are achievable in real operations. In this thesis, the FAF is treated not only as a waypoint in the procedure but also as the place where formal design intentions and operational realities intersect.

Each one of the four aforementioned segments serves as a specific operational purpose. This thesis excludes the missed approach phase and analyses atypical approach states from the initial approach through the final approach, ending shortly before touchdown.

During the three above-mentioned segments, the Minimum Obstacle Clearance (MOC), maximum descent gradients, speed limitations per aircraft category, and procedure design gradients guarantee a safe and stabilised flight profile. ICAO *Doc 8168* underlines the principle of the stabilised approach, requiring aircraft to be fully configured and stabilised in speed, descent rate, and alignment by 1,000 feet above the aerodrome level under Instrument Flight Rules (IFR). IFR is a set of rules that pilots use to fly mainly by the instruments within the cockpit, without needing to look outside. The criteria are fundamental to assessing whether the published arrival design supports operational stability. Aircraft are divided into five categories (A–E) according to their indicated airspeed at the runway threshold (*Vref*) or 1.3 × stall speed in the landing configuration, as summarised in Table 1:

Table 1 Minimum Airspeed Aircraft Category

Aircraft Category	Speed (IAS)	Aircraft type
A	< 91 kt	Light General Aviation aircraft
B	91 – 120 kt	Regional Turboprops
C	121 – 140 kt	Medium Jets (B737, A320)
D	141 – 165 kt	Large Jets (B767, A330)
E	166 – 210 kt	High-performance military or transport jets

Design parameters also include descent gradient and speed limitations, which are derived from these categories to ensure obstacle clearance and flyability for all eligible aircraft types using the procedure.

The vertical profile of the approach is controlled by maximum and minimum descent gradients. For a precision approach, the vertically guided approaches, a standard glide path of 3° is recommended by ICAO, which in theory allows for a stable transition from instrument to visual reference near 200-300 feet Above Ground Level (AGL). The minimum obstacle clearance varies by segment: the 300 m (984 feet) in the **initial** approach segment, the **intermediate** segment requires 150 m (492 feet), and 75 m (246 feet) in the **final** approach segment. It is important to note that during the **intermediate** segment descent gradient should not exceed 5% with a minimum segment length of 5 NMs to facilitate deceleration and configuration. EHAM is situated in a notably flat and low-lying region, with much of the surrounding terrain located below mean sea level. This geographical characteristic, combined with stringent national regulations related to both aviation safety and flood-control infrastructure, results in very limited terrain variation around the airport.

According to the LVNL's electronic Aeronautical Information Publication (eAIP), specifically the obstacle charts AD 2.EHAM-AOC-18C/36C and AD 2.EHAM-AOC-18R/36L, the approach and departure paths to these runways are largely free of significant obstacles (LVNL, 2025). The published obstacle elevations remain well below the defined Obstacle Limitation Surfaces (OLS), indicating that the airport's immediate environment does not present any terrain or man-made structures that would influence the design or application of obstacle clearance criteria.

<u>International Air Transport Association</u>

The importance of maintaining a stable approach despite such constraints is emphasised in the safety risk mitigation strategies published by the International Air Transport Association (IATA, 2016). (IATA, 2016) establishes a structured framework for managing the risk of approach and landing accidents, which remain the most frequent phase of flight accidents in commercial aviation. Between 2011 and 2015, IATA's Global Aviation Data Management database recorded that approximately 65% of all accidents occurred during approach and landing, with unstable approaches contributing to fourteen per cent of these events. The report defines an unstable approach as a significant deviation from target parameters such as flight path, airspeed, rate of descent, thrust setting, and configuration, any of which compromises predictability and safety.

IATA's guidance sets out a globally recognised Stabilised Approach Concept, which requires aircraft to meet defined stability criteria by a specific altitude, typically 1,000 ft above aerodrome level in IFR conditions, or 500 feet in visual conditions, and to maintain these parameters until touchdown. This approach is supported by complementary policies such as mandatory go-around procedures, clear standard operating procedures, and the use of flight data monitoring to identify and mitigate non-compliance. The framework further highlights the role of crew resource management, standard callouts, and safety culture, arguing that consistency and open communication between pilots, controllers, and operators are essential to reduce the rate of unstable approaches.

IATA identifies instability as an undesired aircraft state within the Threat and Error Management (TEM) model (IATA, 2016). It states that unstable approaches often originate from excessive energy conditions arriving too high, too fast, or both, combined with late descent clearances, challenging ATC vectoring, or procedural constraints such as noise abatement profiles. The report prescribes for a multi-layered mitigation strategy involving both pilots and air traffic controllers, emphasising early energy management, improved descent planning, and the avoidance of tactical clearances that undermine stabilisation. Within the context of this thesis, the IATA framework provides an operational safety benchmark that connects the energy-based approach model with recognised industry criteria for stability, forming a reference point for assessing whether approaches to runways 18R and 18C meet the conditions required for safe stabilisation before entering the FAF.

VEMMIS

LVNL's VEMMIS database is the primary surveillance and monitoring platform used to record operational flight data at EHAM. VEMMIS integrates information from radar sensors and Mode S / Enhanced Surveillance (EHS) transponders and stores time-stamped state vectors for each aircraft under control. VEMMIS provides a high-resolution description of the four-dimensional (4D) trajectory: position (latitude, longitude), altitude and time, complemented by kinematic variables such as speed, heading and rate of climb or descent.

For each flight, VEMMIS records a sequence of measurements, where each row corresponds to a radar update at a given time. The data structure used in this study contains flight identifiers, timing information, horizontal and vertical position, Mode C altitude, selected EHS parameters (where available), and derived quantities such as wind estimates and along-track distance between successive points. Table 3 summarises the variables available in the VEMMIS export used for this thesis. While the complete export is documented for transparency, only a subset of these variables is used in the analyses presented in this thesis.

Table 2 Vemmis Variables

Column	Description
FLIGHT_ID	Numeric identifier for the flight within VEMMIS (unique per flight in the dataset).
CALLSIGN	Aircraft callsign as used in ATC communications (e.g. DAL132).
T0	Reference time associated with the flight in VEMMIS (e.g. initial system time stamp).
T_START	Start time of the extraction window for this flight.
TIME	Relative time stamp in seconds from T_START for each radar point.
actual_time	Absolute time stamp of each radar point (datetime).
X, Y	Horizontal position in local Cartesian coordinates in the LVNL reference frame.
lat, lon	Geodetic latitude and longitude of the aircraft position [deg].

MODE_C	Mode C altitude code received from the transponder [hundreds of feet].
ALT	Processed barometric altitude of the aircraft [ft].
EHS_SPD	Mode S Enhanced Surveillance ground speed [kt] (where available).
EHS_IAS	Mode S Enhanced Surveillance indicated airspeed [kt] (where available).
EHS_HDG	Mode S Enhanced Surveillance magnetic heading [deg] (where available).
EHS_ROLL	Mode S Enhanced Surveillance bank angle [deg] (where available).
EHS_ROCD	Mode S Enhanced Surveillance rate of climb/descent [ft/min] (where available).
EHS_TAS	Mode S Enhanced Surveillance true airspeed [kt] (where available).
EHS_MACH	Mode S Enhanced Surveillance Mach number (where available).
RADAR	Identifier of the radar sensor or sector providing the measurement (e.g. ARTAPP, ARTACC).
CLC_WSPD	Computed local wind speed at aircraft position [kt] (where available).
CLC_WDIR	Computed local wind direction at aircraft position [deg] (where available).
distance_to_next	Along-track distance to the next radar point in the trajectory [NM or km, depending on configuration].

In the subsequent analysis, the variables actual_time, lat, lon, ALT and distance_to_next are primarily used to reconstruct the 4D arrival trajectories and derive horizontal and vertical profiles. Where present, the EHS fields (EHS_SPD, EHS_IAS, EHS_HDG, EHS_ROCD, EHS_TAS, EHS_MACH) provide additional detail on speed control, turn dynamics and vertical rates, complementing the purely positional information.

The theoretical framework of this thesis integrates the formal design principles of instrument approach procedures with the operational practices governing their execution during approach operations at runways 18C and 18R, as well as the energy-based interpretation of aircraft approach stability derived from van Renssen's (2025) thesis. Together, these elements form the conceptual foundation for analysing how variations in arrival trajectories between the IAF and the FAF may result in atypical approach states at EHAM.

The design of instrument approach procedures is defined by ICAO Doc 8168, which provides the geometric and operational criteria required to construct safe, predictable, and flyable routes from the en-route phase towards the runway. The framework specifies the structure of the **initial**, **intermediate** and **final** approach segments, each with its own set of specifications. These functions include lateral alignment, altitude management, obstacle clearance and the establishment of a stabilised approach path. The criteria consist of permissible descent gradients, minimum altitudes, speed envelopes and turning radii based on aircraft performance categories that range from A to E.

ICAO *Doc 8168* defines the theoretical conditions under which an approach procedure can be safely flown. It assumes that the aircraft follows the published path without tactical changes, that traffic density does not require dynamic intervention and that no additional vectoring or speed adjustments are needed. At complex airports such as EHAM, where aircraft operate within a tightly managed flow structure, controllers regularly apply tactical measures for sequencing, spacing or energy management. For this reason, the theoretical design cannot be interpreted as a direct representation of operational reality. Instead, it serves in this thesis as a formal baseline against which actual flight trajectories are later evaluated.

Nighttime arrivals at EHAM on runways 18R and 18C (22:00–06:00 local time) utilise three designated IAFs: ARTIP, RIVER, and SUGOL. Each transition leads traffic onto a defined lateral path that converges at NIRSI, which marks the transition into the **Intermediate Approach Segment**. The published characteristics of these routes, such as track length and the associated altitude window define the theoretical vertical demand placed on arriving aircraft before NIRSI. Table 4 summarises the resulting track distance, altitude change, and the implied average descent gradient for each transition. Notably, the SUGOL transition is substantially shorter than ARTIP and RIVER, implying a markedly higher average descent gradient to meet the same altitude constraint at NIRSI; this difference motivates the later assessment of whether certain transitions indirectly impose higher-energy or less stable approach conditions.

Table 3 Published IAF Transitions to Waypoint NIRSI

IAF Transition	Track Distance (NM)	Altitude Change (ft)	Average Gradient (%)	Descent Angle (°)
ARTIP NIRSI	47.0	14,000 → 5,500	2.97	1.7
RIVER NIRSI	43.6	14,000 → 5,500	3.18	1.8
SUGOL NIRSI	27.3	14,000 → 5,500	5.10	2.9

Figure 3 shows the published night-transition arrival routing to runway 18R at EHAM from the three designated IAFs: ARTIP, RIVER, and SUGOL. Each transition follows a defined lateral path with published leg distances and headings, and applies common altitude/speed constraints, before the routes merge at waypoint NIRSI, which serves as the entry into the intermediate approach segment. From NIRSI, the procedure continues via the subsequent fixes toward the final approach for runway 18R (including the depicted FAF reference), illustrating how different entry points result in different track lengths and therefore different implied descent demands to meet the same constraint at NIRSI.

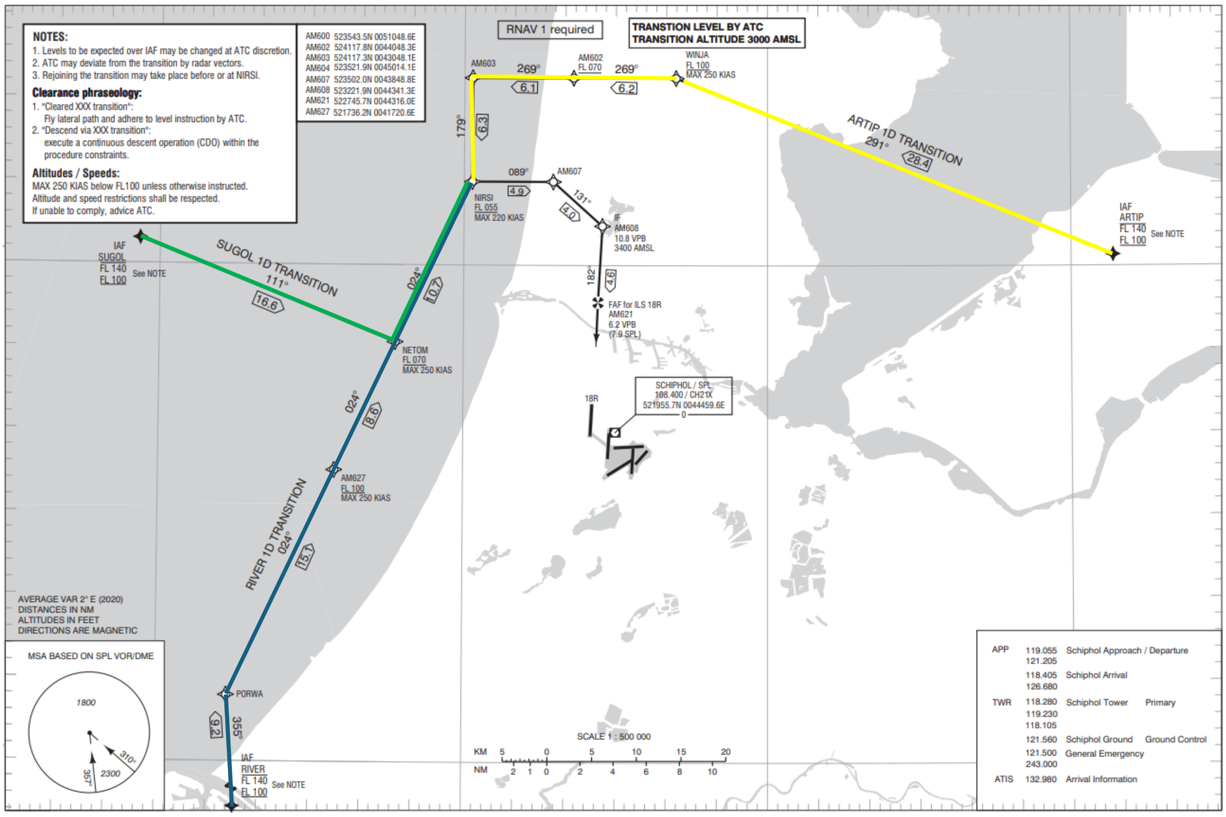


Figure 3 EHAM STAR Night Transition to ILS Runway 18R (LVNL, 2025)

The ARTIP transition is defined through the waypoints WINJA, AM602 and AM603 before converging at NIRSI. In the published night transition chart, this routing is depicted in yellow in Figure 3. The procedure specifies an altitude window between 14,000 feet and 10,000 feet at ARTIP, a maximum speed of 250 knots below 10,000 feet at WINJA, and a minimum altitude of 7,000 feet at AM602. At NIRSI, the published minimum altitude is 5,500 feet. The corresponding track distance between ARTIP and NIRSI is approximately 47.0 NMs, which forms the geometric basis for the intended vertical and lateral structure of this segment of the arrival route.

The transition from SUGOL consists of two legs leading toward NIRSI and is depicted in green in Figure 3. The published procedure specifies that aircraft cross SUGOL between 14,000 feet and 10,000 feet before continuing toward NETOM, where a minimum altitude of 7,000 feet and a maximum speed of 250 knots apply. The track distance from SUGOL to NETOM is approximately 16.6 NMs, after which the route turns toward NIRSI along a segment of about 10.7 NMs. The combined lateral and vertical structure of these legs defines the intended descent path from SUGOL to NIRSI as published in the night transition chart.

The RIVER transition is depicted in blue in Figure 3 and proceeds from RIVER through the waypoints PORWA, AM627 and NETOM before converging at NIRSI. The published procedure specifies an altitude window between 14,000 feet and 10,000 feet at RIVER, followed by a minimum altitude of 10,000 feet at AM627 and 7,000 feet at NETOM. The total track distance between RIVER and NIRSI is approximately 43.6 NMs and defines the intended lateral and vertical structure of this arrival transition, as shown on the night transition chart.

Following the convergence at NIRSI, both runways 18R and 18C use AM607 and AM608 to guide aircraft into the **intermediate** approach segment. At AM608, a minimum altitude of 3,400 feet marks the official beginning of this segment. From there, the aircraft continues toward the FAF. The design gradients for this portion of the approach are summarised in the table below:

Table 4 From NIRSI to FAF

Runway	NIRSI to FAF (Distance in NM)	Altitude Change (ft)	Average Gradient (%)	Descent Angle (°)
18R	13.5	5,500 → 2,000	4.27	2.44
18C	15.4	5,500 → 3,000	2.67	1.53

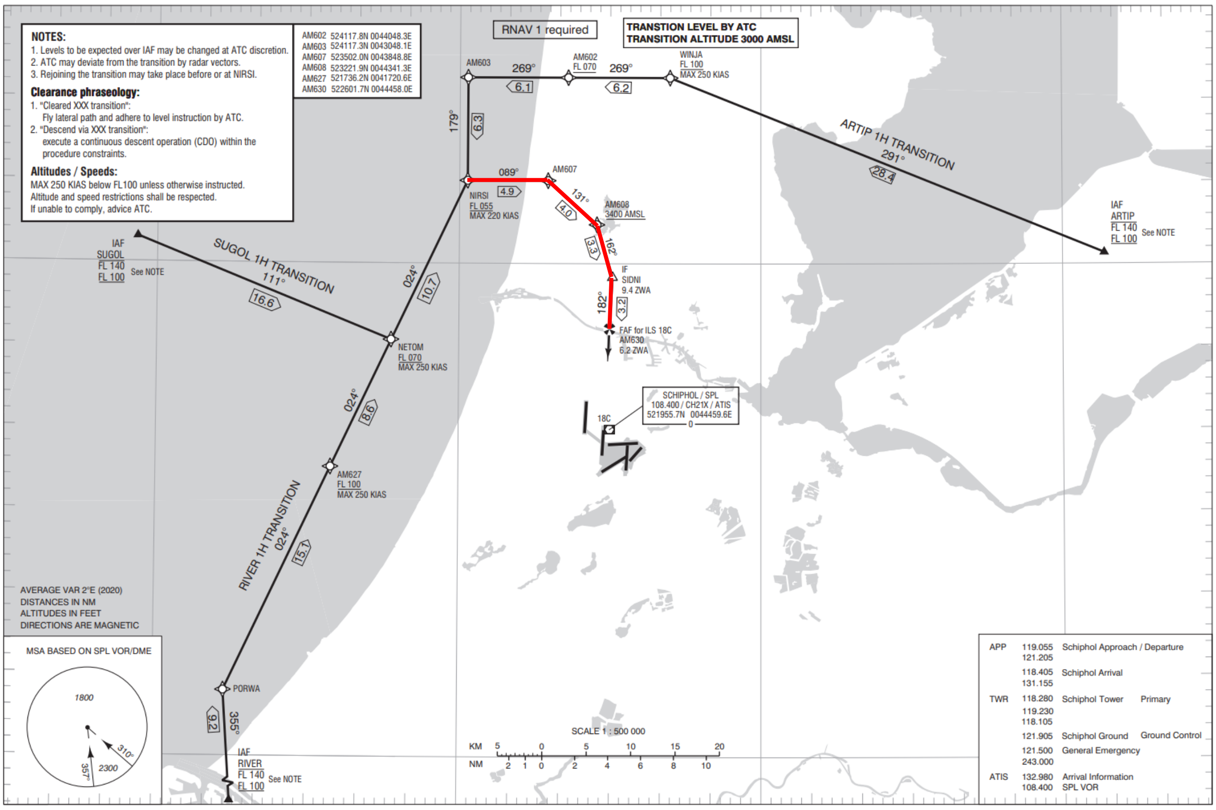


Figure 4 EHAM STAR Night Transition to ILS Runway 18C (LVNL, 2025)

The published transition from NIRSI toward runway 18R proceeds via AM607 to AM608, where the **intermediate** approach segment begins at a minimum altitude of 3,400 ft, as shown in Figure 4. From AM608, the route continues toward FAF at AM621. The published distance between NIRSI and the FAF is approximately 4.6 NMs, defining the vertical and lateral structure of the **intermediate** segment for runway 18R.

For runway 18C, the routing from NIRSI follows AM607 and AM608 before continuing toward SIDNI and the FAF, as illustrated in Figure 5. The distance between NIRSI and the FAF is approximately 6.5 NMs, reflecting the published geometry of the intermediate and final approach alignment for this runway.

The published paths outline the formal design of the **intermediate** and **final** approach segments for runways 18R and 18C and form part of the geometric reference framework used in this thesis.

To bridge the gap between design criteria and operational reality, this research adopts the energy-based approach framework introduced by Jarry, Delahaye and Nicol (2018), which was applied by Van Renssen (2025) to assess approach behaviour at EHAM on runways 18R and 18C. This framework combines an aircraft's altitude and speed into a single measure of total energy, allowing the identification of deviations that indicate non-stabilised or non-compliant approaches.

In a stabilised approach, the aircraft's total energy should decrease progressively and predictably from the IAF towards the FAF. When this rate of energy reduction is irregular or delayed, the aircraft may enter an atypical state, suggesting that it is not following the intended descent profile. The energy framework, therefore, provides a quantitative basis for assessing approach stability in relation to both design and operational influences.

Building on this concept, this thesis uses the established data found by van Renssen (2025) to evaluate approach conformity and atypicality on aircraft before entering the FAF. Atypicality is significantly correlated with the following identifying criteria:

horizontal approach path deviation exceeding one dot on the localiser scale, bank angle exceeding 30°, vertical approach path deviation exceeding one dot on the glide path, and vertical speed exceeding 1,000 feet per minute.

These parameters describe the physical state of excessive or irregular energy states during the approach. Each criterion represents a form of deviation that undermines stabilisation and increases the likelihood of a go-around or an unstable approach event. Within this framework, atypicality is therefore treated as an observable outcome of how aircraft energy management interacts with both procedural design and operational constraints between the IAF and the FAF.

Complementing the energy perspective, the Stabilised Approach Concept defined by the International Air Transport Association (IATA, 2016) provides an operational safety benchmark. It specifies that by 1,000 feet above aerodrome level in instrument conditions, or 500 feet in visual conditions, aircraft must be fully configured for landing with stable speed, descent rate, and flight path. Approaches that fail to meet these conditions are categorised as unstable and should lead to a go-around.

3. Methodology

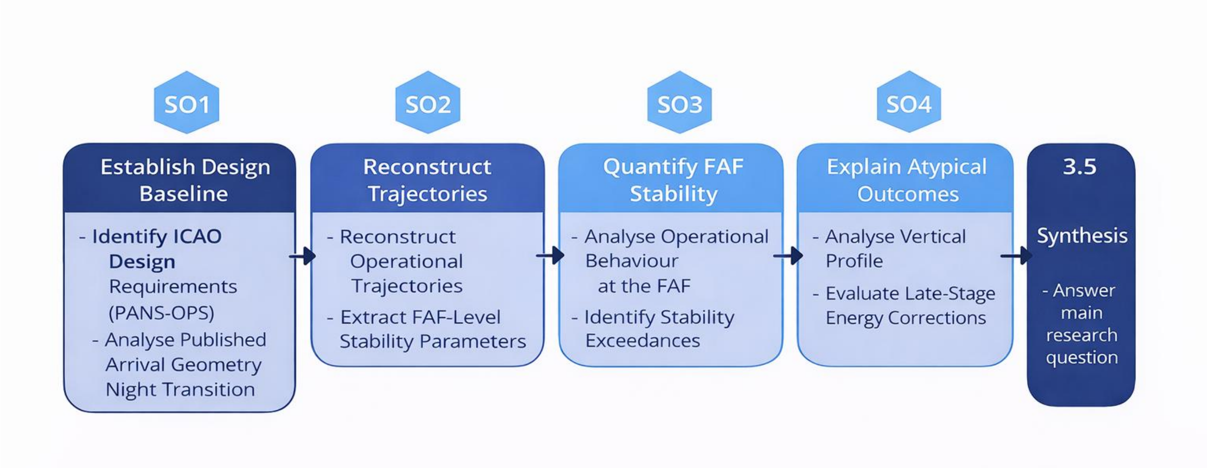


Figure 5 Flowchart Thesis Conceptual Methodology Structure

This thesis is structured as a sequence of five analytical stages, illustrated in Figure 5. The first stage establishes the design baseline by evaluating the geometric and vertical characteristics of the published arrival procedures to runways 18R and 18C against ICAO PANS-OPS criteria. This provides the reference framework against which operational behaviour is assessed.

The second stage reconstructs operational arrival trajectories using surveillance data from LVNL's VEMMIS database. Aircraft trajectories are processed to derive consistent geometric and kinematic parameters, and each flight is reduced to a single representative observation at the FAF. In the third stage, these FAF-level observations are used to characterise operational behaviour and to identify stability-related exceedances across runways and arrival streams.

The fourth stage focuses on vertical profile characteristics and energy management, examining how upstream vertical state and late-stage corrections influence vertical deviation and deceleration behaviour during the final approach segment. The final stage synthesises the design, operational, and energy-based findings to support interpretation of whether observed deviations near the FAF reflect structural characteristics of the arrival design or operational factors arising during execution.

Together, these stages provide a coherent framework for linking intended procedure design to observed operational outcomes, forming the basis for the results and discussion presented in Chapter 4.

3.1 Baseline design requirements

This section outlines the analytical approach used to evaluate the compliance of the three IAF transitions with the design criteria defined in ICAO Doc 8168 (PANS-OPS). The objective of this analysis is to assess the vertical and horizontal geometry of the approach routes, together with their associated altitude and speed constraints, *to* determine whether each transition conforms to the prescribed operational and design standards. The evaluation criteria were derived directly from the specifications contained in ICAO Doc 8168 (PANS-OPS). The reference gradients applied to assess compliance are presented in Table 3.

Table 5 Approach Gradients

Approach Segment	Optimum Gradient	Maximum Gradient
Initial Approach Segment	4 %	8 %
Intermediate Approach Segment	5.2%	5.2 %
Final Approach Segment	5.2 %	6.5 %

3.1.1 Evaluation Initial Approach Fixes to waypoint NIRSI

The limits obtained from ICAO Doc 8168, described in Table 3, were used as benchmark values when assessing the vertical profiles of the ARTIP–NIRSI, RIVER–NIRSI, and SUGOL–NIRSI transitions. The analysis used the published waypoint coordinates, altitude constraints, and track information from the official EHAM ILS runway 18R and 18C transition charts (Figures 3 and 4). For each transition, the total track distance and the altitude change between the start of the transition and NIRSI were used to quantify the implied descent demand.

To derive comparable descent metrics across transitions, the altitude difference Δh was first computed using Equation (1). This altitude change, together with the published horizontal track distance D, was then used to calculate: (i) the average descent gradient Gin percent (Equation (2)), (ii) the equivalent descent demand in feet per nautical mile R(Equation (3)), and (iii) the corresponding descent angle θin degrees (Equation (4)). These metrics are reported in Table 4 and are used in the subsequent discussion to compare the relative steepness of each transition and its potential implications for achieving a stabilised approach before the intermediate segment.

Altitude Difference

The term Δh represents the change in altitude over the analysed segment. It is calculated as the difference between the altitude at the start of the segment and the altitude at the end of the segment, with equation (1) being in feet:

$$\Delta h = h_{start} - h_{end} \quad (1)$$

Vertical Gradient (%):

$$\mathrm{G} = \frac{\Delta h}{D \times 6076.12} \times 100 \quad (2)$$

Where G is the descent gradient given as a percentage, $\Delta \mathrm{h}$ is the altitude difference in feet, and D is the horizontal track distance in NMs. The constant 6076.12 represents the number of feet in one NM (1 NM = 6076.12 ft). It is used to convert the horizontal distance D from NMs to feet, ensuring that the descent gradient is calculated using consistent units.

Descent per NM (ft/NM):

$$R = \frac{\Delta h}{D} \tag{3}$$

Where R is used to express the required vertical change as a descent demand per nautical mile (ft/NM). While the table reports the average gradient in per cent, ft/NM is a common operational planning metric and provides a more intuitive measure of how much altitude must be lost over each NM along the published transition.

Descent Angle (degrees):

$$\theta = \arctan\left(\frac{G}{100}\right) \tag{4}$$

Where θ converts the average gradient (%) into an equivalent descent angle (in degrees). This representation allows direct comparison with standard "rule-of-thumb" descent angles (e.g., ~3°) and supports a clearer interpretation of how steep each published transition is relative to typical approach and descent geometries.

These values were calculated for the total route distance from each IAF to NIRSI and, separately, from NIRSI to the FAF. The results were compared against the ICAO design limits in Table 3 to assess whether the implied descent demand remains consistent with the PANS-OPS gradient guidance for the corresponding procedure segments. A route is considered acceptable in this context when the calculated descent gradient does not exceed the applicable maximum design gradient for that segment. The assessment, therefore, combines quantitative evaluation of descent geometry with interpretation against procedural design limits to judge whether each IAF transition provides sufficient distance for a stable descent towards NIRSI and, subsequently, to the FAF for runways 18R and 18C.

3.1.2 Evaluation of NIRSI to FAF

The evaluation of the **Intermediate** and **Final Approach Segments** was conducted separately for runways 18R and 18C, using published waypoint coordinates, altitude constraints, and track distances obtained from the official EHAM ILS transition charts. Each analysis covered the portion of the approach extending from NIRSI to the FAF, incorporating the intermediate waypoints AM607 and AM608, which define the transition between the **Intermediate** and **Final Approach Segments.**

The evaluation process involved extracting the relevant altitudes and distances from the published approach charts and applying the above formulas to compute the corresponding descent gradients and angles.

For both runways, the analytical procedure followed the same calculation methods described in Section 3.1.1. The descent gradient (*G*), descent per NM (*R*), and descent angle (θ) were determined using Equations (2), (3), and (4), respectively. These parameters were applied to characterise the vertical geometry of the intermediate and final approach profiles.

By conducting separate analyses for each runway, differences in route geometry and segment length could be captured and quantitatively assessed. This ensured that both approaches were evaluated on a comparable methodological basis, allowing subsequent interpretation of how variations in horizontal distance influence the overall descent geometry and compliance with ICAO standards.

3.2 Describing Operational Practices

The second objective of this thesis consists of a data-driven analysis of aircraft behaviour during the approach to runways 18R and 18C, with a specific focus on conditions in the vicinity of the FAF. This phase describes how operational trajectory data were extracted from LVNL's VEMMIS database, processed using Python, and reduced to a set of stability-related parameters and atypical conditions used in the subsequent analyses.

The analysis focuses primarily on daytime operations, for which a large and statistically robust dataset is available. All data processing, geometric reconstruction, and statistical analysis were performed in Python using vectorised operations to ensure numerical consistency and computational efficiency.

3.2.1 Data ingestion and trajectory preparation

Operational surveillance data were obtained from the VEMMIS database, which integrates radar and Mode S Enhanced Surveillance (EHS) measurements to provide time-stamped state vectors for each aircraft. For each flight, VEMMIS records a sequence of radar updates indexed by a unique *FLIGHT_ID*, with each row representing the aircraft state at a specific time.

VEMMIS export files were loaded and concatenated into a single dataset using Python. Records were sorted by *FLIGHT_ID* and absolute time (*actual_time*) to ensure that each flight is represented as a strictly time-ordered trajectory. The primary variables used for trajectory reconstruction are geodetic position (*lat*, *lon*), processed barometric altitude (*ALT*), and time. Where available, EHS parameters such as indicated airspeed (*EHS_IAS*), rate of climb or descent (*EHS_ROCD*), magnetic heading (*EHS_HDG*), and bank angle (*EHS_ROLL*) were used to directly characterise aircraft kinematics. When EHS parameters were unavailable, equivalent quantities were derived from positional and temporal differences between successive radar points.

To compute along-track distance, cross-track deviation, and bearing geometry consistently, the surveillance positions could not be used directly in latitude/longitude. Degrees of latitude and longitude are not linear distance units, and the metres-per-degree relationship varies with latitude; using them directly would therefore distort distance and angle calculations. The trajectory points were therefore transformed to a local Cartesian coordinate system (eastings x, northings y in metres) using an equidistant local projection centred on the EHAM runways 18C and 18R reference point. Over the relatively small spatial extent of the approach area (tens of nautical miles), this local planar approximation introduces negligible distortion while enabling straightforward Euclidean calculations. In this Cartesian frame, distances between successive radar points, along-track distance to the runway/FAF, and cross-track displacement relative to the runway centreline were computed and used in the subsequent analyses.

3.2.2 Runway assignment and runway-aligned reference frame

Runway thresholds for runways 18R and 18C were projected into the same Cartesian reference frame. A runway-aligned axis was constructed using the published runway heading of 182°, providing a common reference for both along-track and cross-track calculations.

Runway assignment was performed at flight level to ensure a single runway label per arrival. For each *FLIGHT_ID*, the final recorded position in the approach segment was compared geometrically to the projected runway thresholds. The runway whose threshold was closest was assigned as the arrival runway ("18R" or "18C"), and this assignment was propagated to all trajectory points belonging to that flight.

Using the runway-aligned axis, along-track distance was computed as the projection of the aircraft position vector onto the runway axis, while cross-track distance was computed perpendicular to this axis. These quantities form the basis for the derivation of ILS localiser deviation and for identifying the aircraft's longitudinal position relative to the FAF.

3.2.3 Derivation of ILS dot-equivalent deviations

ILS tracking performance was expressed using dot-equivalent metrics to enable consistent comparison across runways and aircraft types.

Horizontal deviation (localiser) was derived by converting the cross-track distance from the runway axis into a dot-equivalent deviation using a standard scale of 0.35 NM per dot. This yields a signed deviation in dots, with positive and negative values indicating displacement to either side of the runway centreline.

Vertical deviation (glideslope) was taken directly from VEMMIS when an ILS glideslope deviation field was available. When unavailable, vertical deviation was computed geometrically from the aircraft's altitude above the runway threshold (*ALT*) and its along-track distance. The implied glide-path angle was compared to the nominal 3° glideslope, and the angular difference was converted to dot-equivalent deviation assuming 0.35° per dot. This approach ensures a consistent definition of vertical deviation across the dataset and avoids dependence on avionics-specific signal reporting.

3.2.4 FAF definition and extraction of a representative FAF observation

The FAF for each runway was defined using its published geographical coordinates. For each trajectory point, the distance to the appropriate FAF was computed. Points within a fixed proximity of the FAF were considered valid points to ensure a consistent FAF definition across all trajectories. The nearest point within a radius of 250m was used as the FAF observation, which has been visually represented in Figure 6.

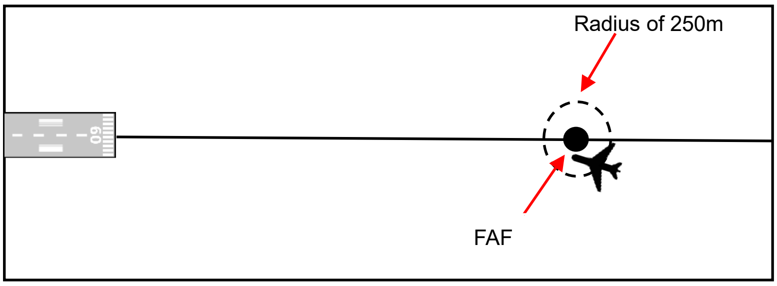


Figure 6 FAF Radius capture

For each flight, the trajectory point within this radius that minimised the distance to the FAF was selected as the representative FAF observation. To ensure that this observation reflects established final approach conditions, candidate points were additionally required to be aligned with the runway axis within a practical tolerance. Flights for which no valid FAF observation could be identified were excluded.

The resulting FAF-level dataset contains one observation per flight and includes the assigned runway, arrival stream, calibrated airspeed, vertical speed, bank angle, altitude, and horizontal and vertical ILS deviation expressed in dot-equivalents.

3.2.5 Classification by arrival stream

To relate FAF behaviour to upstream arrival structure, each flight was classified by entry route based on the published Initial Approach Fixes ARTIP, RIVER, and SUGOL. For each flight, the full trajectory was compared to the three IAF coordinates using great-circle distance, and the flight was assigned to the IAF to which it came closest at any point along its track. This categorical variable (*entry_route*) was merged into the FAF-level dataset.

3.2.6 Definition of stability parameters and exceedance flags

To describe operational practices in a manner consistent with approach stability concepts, binary exceedance flags were defined at the FAF for a set of stability-related parameters.

The exceedance thresholds were defined as:

- Bank angle > 30°
- Descent rate ≥ 1,100 ft/min
- Lateral deviation > 1 dot
- Vertical deviation > 1 dot

Because each flight contributes a single FAF observation, exceedance rates can be interpreted directly as the proportion of arrivals crossing the FAF in a condition exceeding the defined threshold.

3.3 FAF-Based Operational Behaviour Characterisation

This section describes how the reconstructed trajectories were reduced to a single, comparable observation per flight at the FAF and how these observations were used to characterise operational behaviour across runways and arrival streams.

Using the FAF-level dataset described in Section 3.2, each arrival contributes exactly one observation representing the aircraft's state during the transition from intermediate to final approach. This reduction is essential to avoid temporal autocorrelation within trajectories and to ensure that statistical summaries reflect flight-level behaviour rather than individual radar updates.

FAF-level parameters include calibrated airspeed, vertical speed, bank angle, altitude, and horizontal and vertical ILS deviation expressed in dot-equivalents. These parameters were selected because they directly correspond to commonly used approach stability criteria and allow consistent comparison between day and night operations and between runways 18R and 18C.

For night-time operations, FAF-level observations were grouped by arrival stream (ARTIP, RIVER, and SUGOL) and by runway to examine whether differences in operational behaviour could be observed at the FAF. Descriptive statistics and distributions were computed to assess vertical speed behaviour, airspeed, bank angle, and ILS tracking performance. This analysis forms the basis for identifying whether deviations observed at the FAF reflect isolated parameter exceedances or broader instability patterns.

For daytime operations, FAF-level observations were used to compute runway-level exceedance rates for each stability parameter. Because each flight contributes a single FAF observation, these exceedance rates can be interpreted directly as the proportion of arrivals crossing the FAF in a condition exceeding the defined threshold. This provides a clear and comparable measure of operational behaviour between runways.

3.4 Identification of Atypical Approach Conditions

This thesis uses two distinct outcome measures, derived from the FAF-level dataset, to characterise approach behaviour. The first outcome describes approach stability at the FAF using threshold exceedances of key parameters at a single, standardised point. The second outcome identifies atypical approach behaviour after the FAF using an energy-management proxy computed over the final approach segment. These measures are complementary: FAF exceedances describe instantaneous stability at the FAF, while the atypical metric captures whether substantial corrections occur between the FAF and the 3 NM stabilisation point.

3.4.1 Stability exceedances at the FAF

Binary exceedance flags were constructed for each stability-related parameter using the thresholds defined in Section 3.2.6. Each flag indicates whether a flight exceeds a specific criterion at the FAF. By evaluating all flights at the same point, the analysis avoids ambiguity associated with transient deviations earlier in the arrival and focuses on conditions most relevant to the stabilisation concept at the start of the final approach.

For daytime operations, exceedance rates were computed separately for runways 18R and 18C by dividing the number of flights exceeding each threshold by the total number of valid FAF observations for that runway. In addition to individual thresholds, combinations of exceedances were evaluated to distinguish isolated deviations from cases where multiple criteria are exceeded simultaneously.

For nighttime operations, exceedance outcomes were analysed descriptively rather than as rates due to the smaller sample size, to identify structural differences in FAF behaviour between runways and arrival streams.

3.4.2 Atypical approach classification after the FAF (daytime)

Atypical approach behaviour was assessed separately from FAF exceedances. For daytime operations, an approach was classified as atypical when the average airspeed reduction between the FAF (6.2 NM) and the 3 NM point exceeded 20 kt per NM (Section 4.3). Speeds at both endpoints were extracted using the nearest available observations within a tolerance band to reduce sensitivity to radar sampling variability. This classification captures late-stage energy dissipation consistent with sharp corrective behaviour during the final approach segment.

3.4.3 Relationship between FAF vertical state and atypical outcomes

To test whether instability at the FAF is associated with downstream corrective behaviour, daytime arrivals were first categorised by FAF vertical state (FAF_HIGH, FAF_ON_ALT, FAF_LOW) relative to the nominal crossing altitude. Conditional atypical rates were then computed as $P(\text{Atypical} \mid \text{FAF state})$for each runway. This establishes whether being high (or low) at the FAF is associated with increased likelihood of atypical energy loss between the FAF and 3 NM, and motivates the subsequent upstream analyses.

3.5 Vertical Profile and Energy-Based Analysis

The final methodological phase focuses on identifying mechanisms underlying vertical deviation and late-stage energy management during daytime operations. This phase builds directly on the exceedance analysis by examining how upstream vertical state and operational conditions before intercept influence behaviour at the FAF and beyond.

3.5.1 Modelling the likelihood of vertical exceedance at the FAF

Because vertical deviation was identified as the dominant exceedance type during daytime operations, the probability of vertical deviation greater than one dot at the FAF was modelled using logistic regression. Separate models were estimated for runway 18R and runway 18C to allow runway-specific interpretation.

Explanatory variables were defined to represent both procedural and operational influences:

- Arrival stream, with RIVER used as the reference category
- Upstream vertical profile gates, representing whether aircraft were below published altitude expectations near ALINA and SIDNI for runway 18C, and near PEVOS for runway 18R
- A binary indicator representing instability in the final 10 NM prior to the FAF

Model coefficients were transformed into percentage change in odds to facilitate interpretation in operational terms. This modelling approach allows assessment of the relative importance of arrival stream geometry, upstream vertical set-up, and late-stage instability in driving vertical exceedance at the FAF.

3.5.2 Threshold-based energy correction analysis

To complement the waypoint-based vertical profile analysis, a threshold-based approach was used to assess whether aircraft delivered with excess vertical energy are more likely to perform sharp energy corrections in the final approach segment.

Aircraft were classified as “high” when their median altitude at selected fixes exceeded predefined thresholds between 2,100 and 2,500 ft. This classification captures situations in which aircraft enter the final approach with elevated vertical energy relative to the expected profile. The altitude thresholds between 2,100 and 2,500 ft were selected as a sensitivity range around the nominal 2,000 ft vertical target used in the **Intermediate**-to-**Final Segment** transition. The lower bound (2,100 ft) represents a small but operationally meaningful exceedance above nominal (≈+100 ft), consistent with the FAF-state tolerance applied elsewhere in the thesis, while the upper bound (2,500 ft) captures a clearly elevated vertical-energy condition (+500 ft) that still occurs in routine operations and remains within the regime where aircraft may attempt to recover through increased descent rate and/or late speed reduction. Evaluating multiple thresholds allows assessment of whether the likelihood of atypical energy-loss behaviour increases progressively with increasing “high” altitude, rather than relying on a single arbitrary cut-off.

The outcome of interest was defined as a sharp deceleration event in the final approach segment, operationalised as a maximum deceleration rate of at least 20 kt per nautical mile over an approximately 1 NM interval between the FAF (6.2 NM) and 3 NM from the runway threshold. For each runway and fix, conditional probabilities of atypical deceleration were computed for aircraft classified as high and not high.

Risk differences and odds ratios were derived to quantify the strength of association between elevated vertical state and late-stage energy correction. This analysis provides insight into whether excess vertical energy carried from upstream segments manifests as operationally relevant corrections close to the runway, and whether these mechanisms differ between runways 18R and 18C.

4. Results and Discussion

This chapter presents and interprets the results of the analysis conducted to assess whether variations between intended and actual arrival paths are associated with atypical approach conditions at Amsterdam Airport Schiphol. The chapter follows the analytical structure established in the methodology and progresses from procedural design characteristics to observed operational behaviour.

Section 4.1 establishes the design baseline of the published night arrival transitions from the Initial Approach Fixes (IAFs) ARTIP, RIVER, and SUGOL to runways 18R and 18C. This section evaluates the vertical characteristics of the published procedures against ICAO PANS-OPS criteria and defines the reference conditions against which operational behaviour is assessed.

Section 4.2 analyses night-time operational behaviour at the Final Approach Fix (FAF) using VEMMIS trajectory data. It examines vertical speed, airspeed, bank angle, and ILS tracking performance to determine whether deviations observed at the FAF reflect unstable aircraft behaviour or structural characteristics inherent to the published night transition geometry.

Section 4.3 extends the analysis to daytime operations, using a substantially larger dataset to quantify exceedance rates of key stability parameters at the FAF and to compare behaviour between runways 18R and 18C.

Section 4.4 focuses on vertical deviation as the dominant atypical condition in daytime operations and evaluates the influence of arrival stream, upstream vertical profile, and late-stage instability using regression modelling and conditional probability analysis. Section 4.4.1 further examines the role of elevated upstream vertical energy in driving sharp energy corrections in the **Final Approach Segment**.

Together, these sections provide an integrated assessment of how design characteristics and operational practices interact to shape approach behaviour at the FAF.

4.1 Night Transition Route Compliance

The published night transition structure described in the theoretical framework (*Section 2.2.1*) establishes the procedural baseline against which operational compliance is assessed. The night arrival transitions from ARTIP, RIVER, and SUGOL to NIRSI, as well as the subsequent routing from NIRSO to the FAF of runway 18C and 18R, are evaluated against the design criteria defined in ICAO *Doc 8168 (PANS-OPS)*. This assessment verifies that the published procedures comply with applicable vertical design limits and defines the reference conditions for the analysis of observed aircraft behaviour.

The theoretical descent gradients of the published routes are summarised in Table 7. These values represent the intended vertical path of each **Initial Approach Segment** and serve as benchmarks against which observed descent profiles are evaluated.

Table 7 shows that the transition from ARTIP to NIRSI and RIVER to NIRSI provides relatively long track distances, resulting in theoretical average descent gradients of 2.97% and 3.18%, respectively. Both values remain below the ICAO optimum planning value of 4% for the **Initial Approach Segment**, as well as well below the maximum permissible gradient of 8%.

Table 6 Theoretical Descent Gradients for IAF Transitions Compared with ICAO Initial Approach Limits

Transition	Track Distance (NM)	Altitude Change (ft)	Theoretical Average Gradient (%)	ICAO Doc 8168 Maximum Gradient for Initial Approach (%)
ARTIP NIRSI	47.0	14,000→5,500	2.97	8.0
RIVER NIRSI	43.6	14,000→5,500	3.18	8.0
SUGOL NIRSI	27.3	14,000→5,500	5.10	8.0

The SUGOL to NIRSI transition offers a shorter track distance, producing a steeper theoretical gradient of 5.10%. This exceeds the ICAO optimum planning value; it remains well within the maximum allowable limit. This indicates that, although SUGOL requires a more concentrated descent, the published geometry remains fully compliant with PANS-OPS design criteria.

These gradients reflect the intended vertical characteristics of the published Initial Approach Segment, which are designed to balance obstacle clearance requirements with manageable aircraft energy reduction before the **Intermediate Approach Segment**.

The intended descent characteristics of the Intermediate Approach Segment from NIRSI to the FAF for runways 18R and 18C are presented in Table 8.

Table 7 Theoretical Descent Gradients from NIRSI to the FAF Compared with ICAO Intermediate Segment Limits

Runway	Distance NIRSI FAF (NM)	Altitude Change (ft)	Theoretical Average Gradient (%)	ICAO Doc 8168 Maximum Gradient for Intermediate Approach (%)
18R	13.5	5,500 2,000	4.27	5.2
18C	15.4	5,500 3,000	2.67	5.2

Table 8 shows the theoretical descent gradient toward runway 18R is 4.27%, while the gradient toward runway 18C is 2.67%, reflecting differences in available track distance between NIRSI and the respective FAFs. Both values remain below the ICAO maximum permitted gradient of 5.2% for the Intermediate Approach Segment. These gradients are therefore compliant with PANS-OPS requirements and consistent to stabilise aircraft before the Final Approach Segment.

The analysis confirms that the published night arrival transition to runway 18R and 18C satisfy all applicable ICAO PANS-OPS vertical design criteria for both the Initial, Intermediate and Final Approach Segments. The procedures are valid and compliant by design.

Importantly, compliance with PANS-OPS criteria establishes the feasibility and safety of the published procedures, but does not imply uniform operational outcomes. The gradients presented in this section, therefore, serve as reference conditions against which actual aircraft trajectories are evaluated in the subsequent analysis.

4.2 Atypical Approaches during Night Time

To evaluate whether night arrival transition influences aircraft behaviour near the FAF, nighttime arrivals to runways 18R and 18C were analysed and grouped by Initial Approach Fix (IAF). The dataset consists of several hundred flights per runway with valid trajectory data in the immediate vicinity of the FAF. These observations form the baseline for assessing approach stability and aircraft behaviour during the transition from the **Intermediate** to the **Final Approach Segment**.

An initial examination of vertical speed profiles indicates that a subset of flights crossed the FAF with descent rates exceeding 1,000 ft/min. While these occurrences are operationally notable, they were observed in isolation and did not coincide with exceedances in calibrated airspeed, bank angle, or ILS tracking performance. Figure 6 shows the distribution of vertical speeds at the FAF by IAF, with the majority of flights clustered between approximately 800 and 1,200 ft/min. Differences between transitions are modest, with ARTIP and RIVER exhibiting similar descent rates and SUGOL showing slightly lower values.

Importantly, higher descent rates above approximately 1,300 ft/min occurred infrequently and were not accompanied by other indicators of instability. This indicates that elevated vertical speeds at the FAF do not, in isolation, constitute atypical or unsafe approach behaviour within the examined dataset.

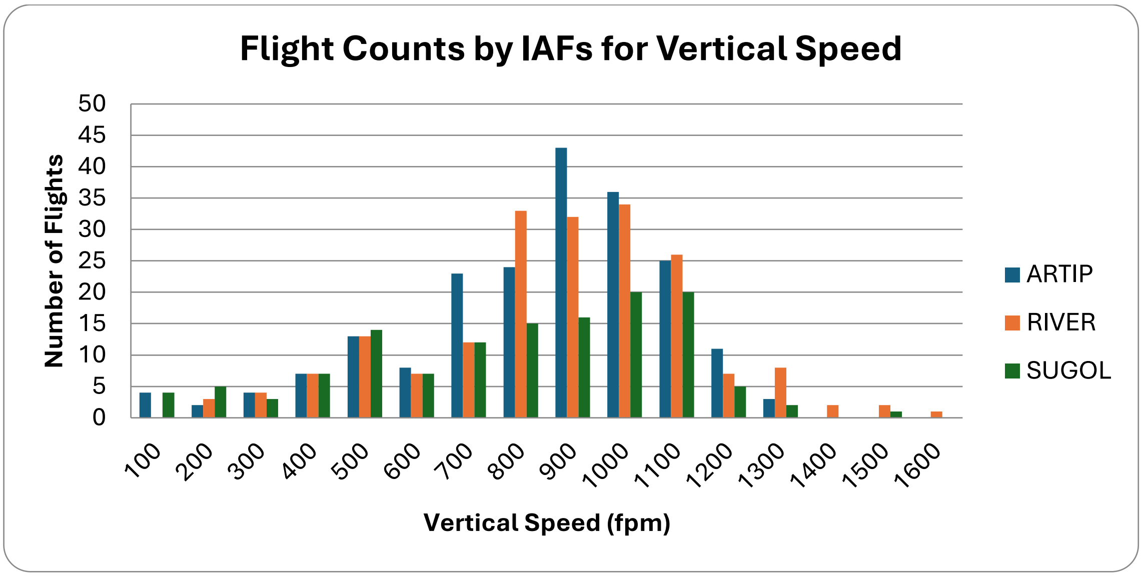


Figure 7 Flight Counts by IAFs for Vertical Speed

Airspeed behaviour at the FAF is similarly consistent. As shown in Figure 7, all observed airspeeds remain within expected operational ranges and below the regulatory limit of 250 kt below 10,000 ft. No systematic differences between IAFs were observed, and no airspeed exceedances indicative of unstable approach conditions were identified.

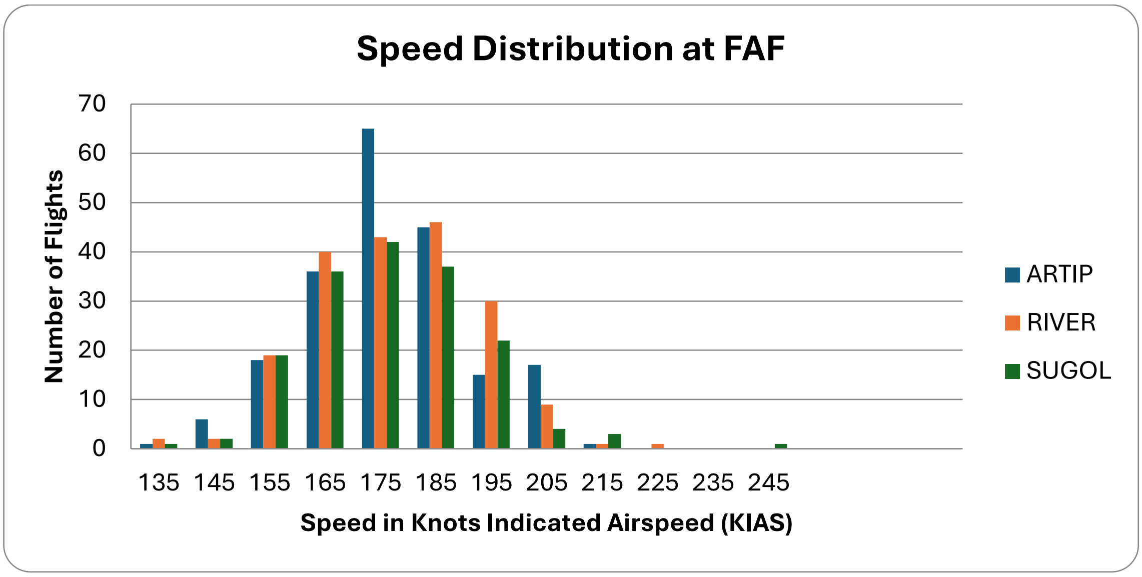


Figure 8 Speed Distribution at FAF

Horizontal ILS deviation at the FAF remained highly stable for both runways. No flights exceeded the ±1 dot threshold, and the distributions shown in Figures 8 and 9 demonstrate tightly clustered lateral deviations. This behaviour is consistent with operational expectations, as localizer capture typically occurs well before the FAF, leaving limited variability by the time aircraft transition onto the **Final Approach Segment**.

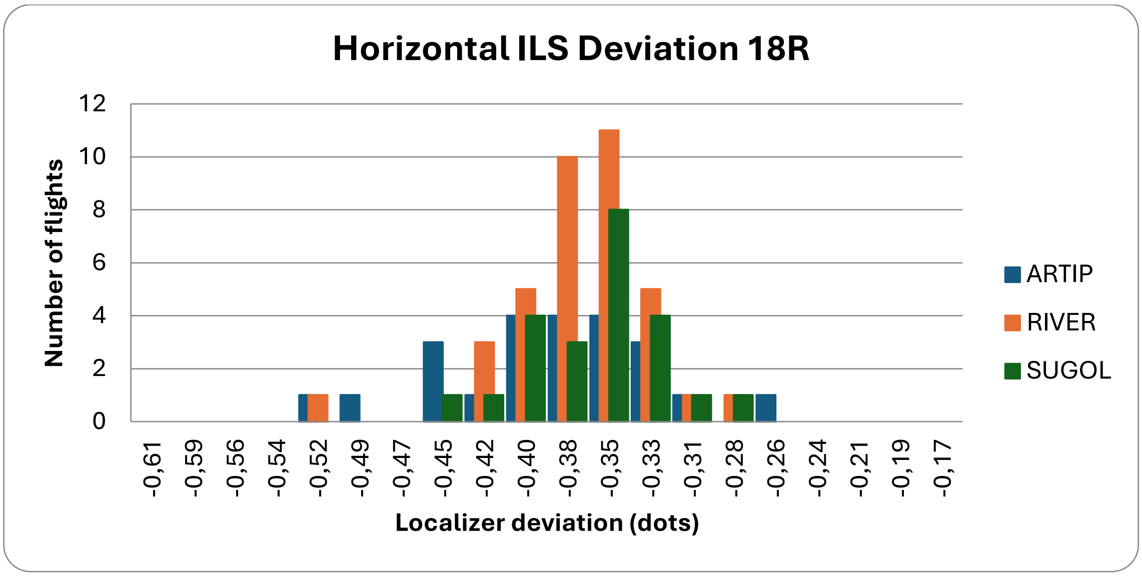


Figure 9 Horizontal ILS Deviation 18R

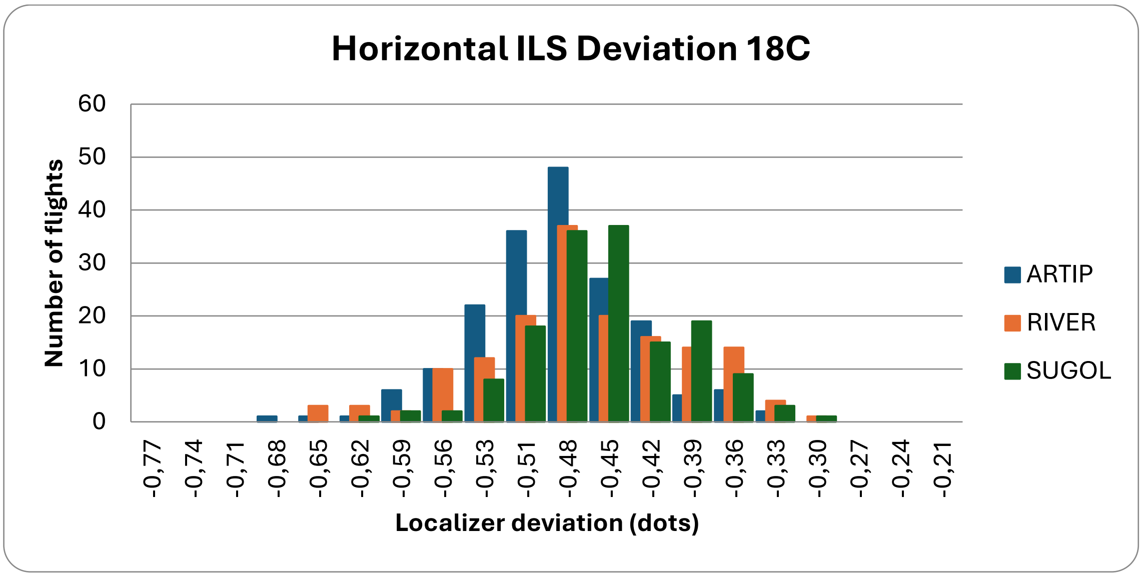


Figure 10 Horizontal ILS Deviation 18C

Vertical ILS deviation at the FAF, expressed in glideslope dots, reveals a clear difference between runways 18C and 18R (Figures 10 and 11). For runway 18C, the distribution is compact and centred close to the nominal glideslope, with most aircraft remaining within approximately ±0.5 dots. Deviations are small and slightly positive, and exceedances beyond one dot are rare. Across all IAFs, the spread remains limited, indicating consistent vertical energy management at the FAF.

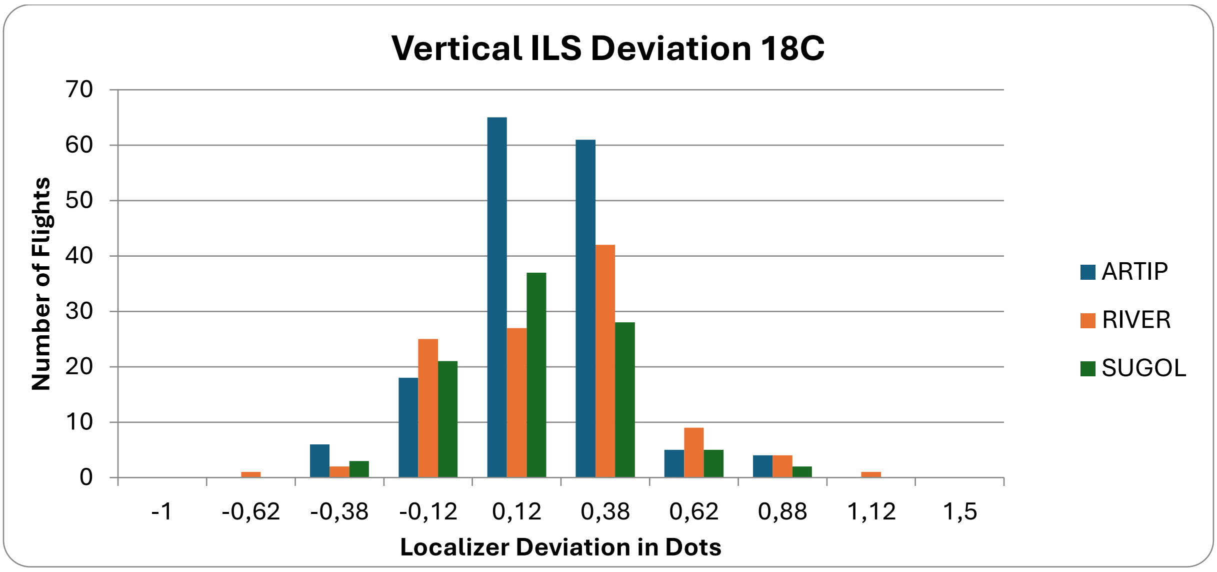


Figure 11 Vertical ILS Deviation 18C

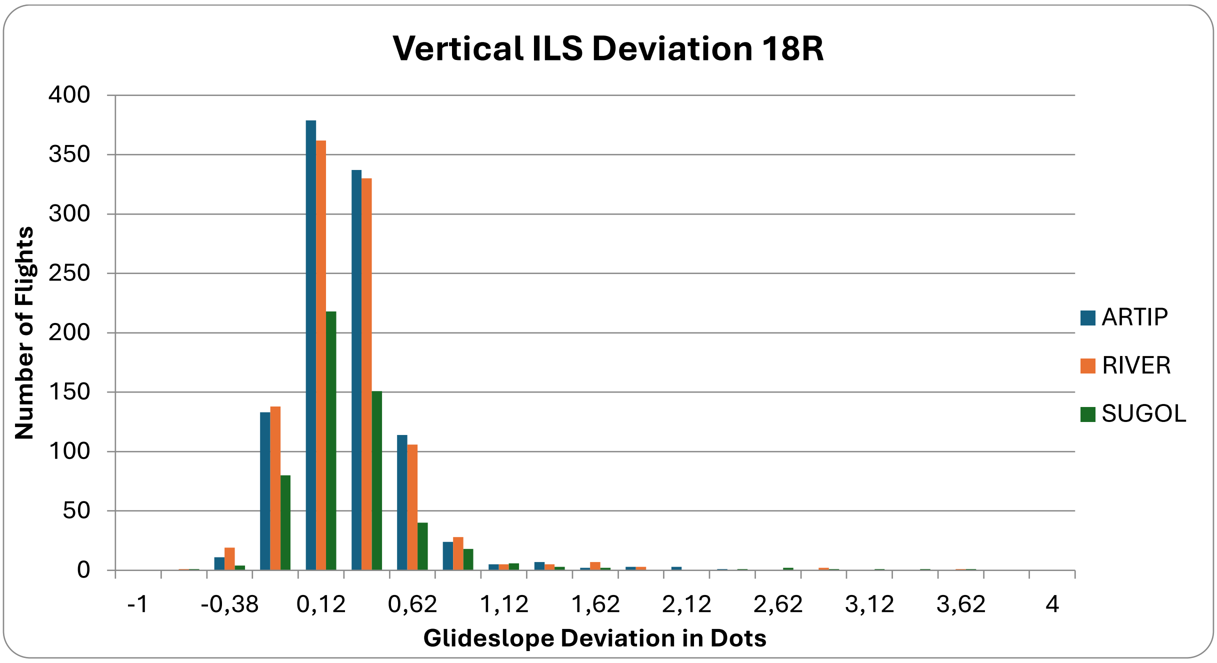


Figure 12 Vertical ILS Deviation 18R

Runway 18R, by contrast, exhibits a broader distribution of vertical deviation. While the central portion of the distribution remains near the nominal glideslope, a small subset of flights crosses the FAF at elevated vertical states. This is reflected in a higher positive dot value, with a limited number of flights exceeding one dot and a smaller subset exceeding two dots. These deviations are predominantly positive, indicating aircraft arriving above the nominal glideslope rather than below it.

Although the majority of flights on runway 18R remain well within nominal limits, the wider spread suggests that vertical conditions at the FAF are more variable than on runway 18C. This increased variability does not indicate a systematic procedural deficiency, but rather reflects a greater sensitivity to upstream conditions, such as arrival geometry, operational constraints, and aircraft-specific energy management.

To determine whether the observed ILS deviations are associated with approach instability or active corrective manoeuvring, correlations were calculated between horizontal and vertical ILS deviation and calibrated airspeed, vertical speed, and bank angle at the FAF. Table 9 summarises the maximum observed correlations for all nighttime approaches and separately for runways 18R and 18C.

Table 8 Maximum Observed Correlations Between ILS Deviation and Other Flight Parameters at the FAF

Dataset	Parameter Pair	Correlation (r)	Interpretation
All Night Approaches	Horizontal vs Vertical ILS Deviation	+0.46	Moderate Positive Association
	Vertical ILS Deviation vs Airspeed	+0.04	No Meaningful Relationship
	Vertical ILS Deviation vs Vertical Speed	+0.12	Very weak Relationship
	Vertical ILS Deviation vs Bank Angle	-0.34	Weak Negative Relationship
Runway 18R	Horizontal vs Vertical ILS Deviation	+0.07	No Meaningful Relationship

	Vertical ILS Deviation vs Airspeed	0.00	No Relationship
	Vertical ILS Deviation vs Vertical Airspeed	+0.23	Weak Relationship
	Vertical ILS Deviation vs Bank Angle	-0.17	Very Weak Relationship
Runway 18C	Horizontal vs Vertical ILS Deviation	+0.04	No Meaningful Relationship
	Vertical ILS Deviation vs Airspeed	0.00	No Relationship
	Vertical ILS Deviation vs Vertical Speed	+0.20	Weak Relationship
	Vertical ILS Deviation vs Bank Angle	+0.13	Very Weak Relationship

Across all datasets, vertical ILS deviation shows no meaningful correlation with calibrated airspeed or vertical speed, and only weak associations with bank angle. This indicates that aircraft crossing the FAF above or below the nominal glideslope are not systematically faster, slower, or descending at higher rates than nominal, nor are they engaged in aggressive manoeuvring.

The only notable relationship in the aggregated dataset is a moderate positive correlation between horizontal and vertical ILS deviation, suggesting that lateral and vertical offsets may share a common upstream influence. The analysis is performed separately for each runway, this coupling largely disappears, reinforcing the interpretation that the deviations are systematic rather than operational in origin.

Taken together, the results indicate that while individual parameter exceedances and statistically observable correlations are present during nighttime arrivals, these occur in an isolated manner. Exceedances in vertical speed, vertical ILS deviation, or other flight parameters were not found to coincide systematically within the same approach. As a result, none of the analysed flights exhibit the combination of deviations that would characterise an atypical state.

Although runway 18R demonstrates greater variability in vertical deviation at the FAF compared to runway 18C, this variability is not associated with unsafe energy states, excessive manoeuvring, or corrective behaviour at the start of final approach. Instead, the observed deviations reflect isolated responses to upstream conditions rather than a breakdown of approach stability.

Based on the analysed nighttime arrivals, no atypical final approaches were identified within the dataset, and no evidence was found that the published night transition routes themselves impose or induce atypical approach behaviour. The results therefore indicate that the night transition design complies not only with procedural criteria, but also with observed operational performance during the transition from **Intermediate** to the **Final Approach Segments**.

4.3 Characteristics of Atypical Day-Time Approaches

To assess whether atypical approach behaviour observed during nighttime operations persists under daytime conditions, daytime arrivals to runways 18R and 18C were analysed in the vicinity of the FAF. A dataset of 51,869 daytime arrivals was obtained, with each flight represented by a single observation corresponding to its state closest to the FAF while established on the final approach heading. This dataset provides a basis for evaluating approach stability under higher traffic density and more dynamic operational conditions than those present during nighttime operations.

Aircraft were classified according to their vertical state at the FAF relative to the nominal crossing altitude of 2,000 ft, using three categories:

- FAF_HIGH (more than 100 ft above nominal)
- FAF_LOW (more than 100 ft below nominal)
- FAF_ON_ALT (within ±100 ft of nominal)

Figure 18 presents the distribution of these vertical states for runways 18R and 18C. For both runways, the majority of arrivals cross the FAF close to the prescribed altitude. On runway 18C, approximately 70% of aircraft are classified as FAF_ON_ALT, with 27% FAF_HIGH and 3% FAF_LOW. A comparable distribution is observed on runway 18R, where 70% of arrivals are FAF_ON_ALT, 28% FAF_HIGH, and 2% FAF_LOW. These results indicate that exposure to elevated or depressed vertical states at the FAF is broadly similar for both runways.

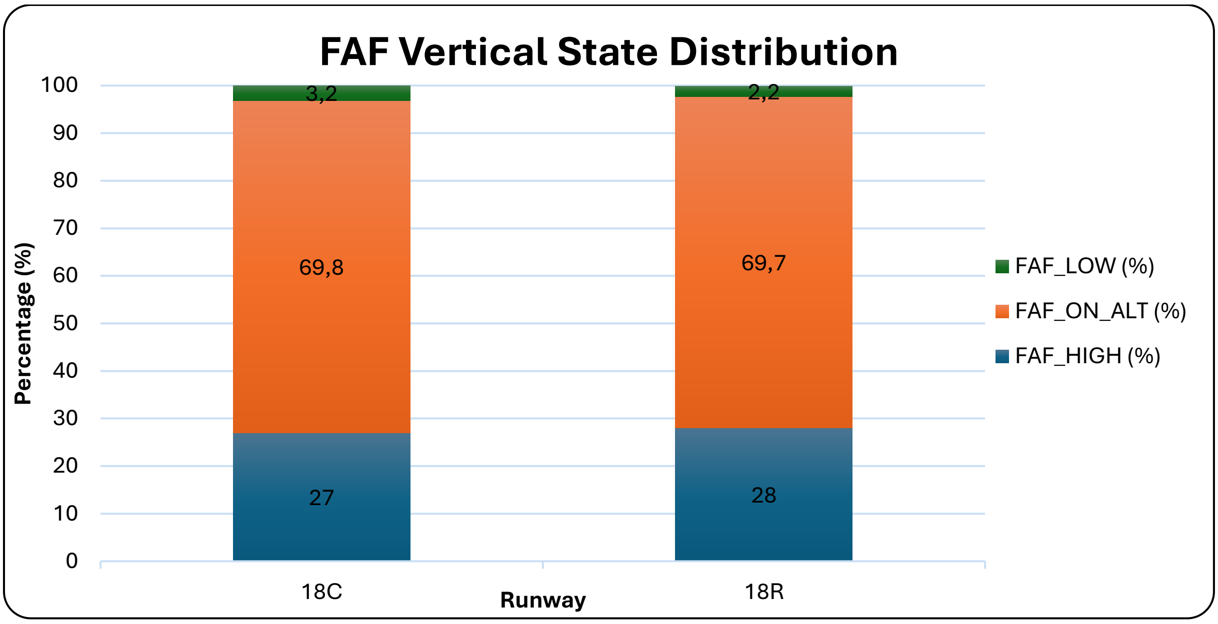


Figure 13 FAF Vertical State Distribution

An approach was classified as atypical if the cumulative total specific energy loss between the FAF and the 3 NM stabilisation point exceeded 20 kt per nautical mile, consistent with the definition applied throughout this thesis. Figure 19 illustrates the proportion of atypical approaches conditional on FAF vertical state for each runway, while Table 10 provides the corresponding atypical rates expressed per 1,000 approaches.

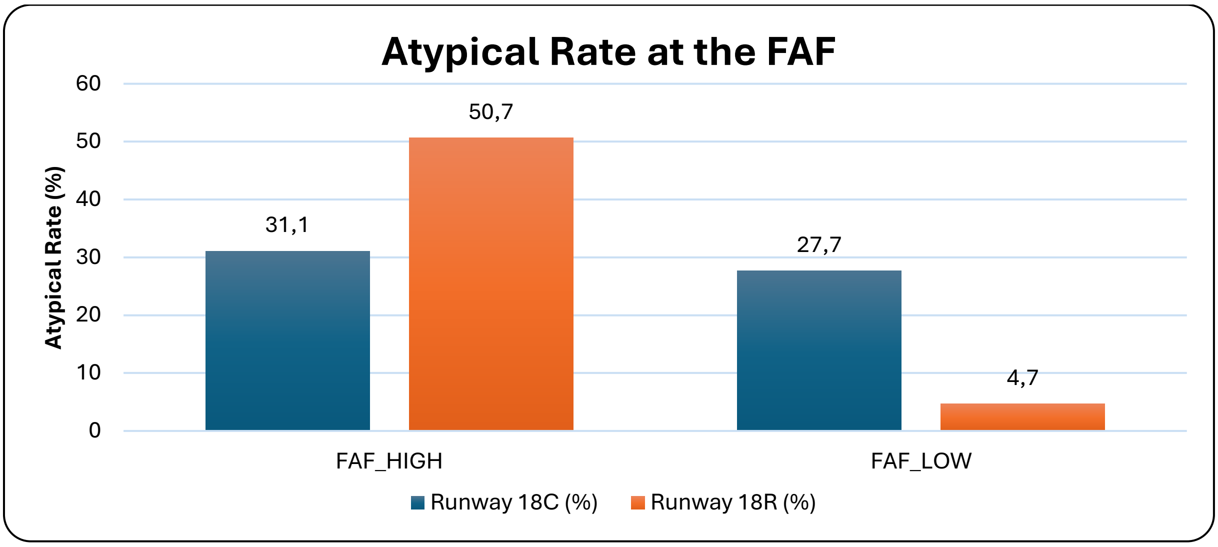


Figure 14 Atypical Rate at the FAF

Table 9 Atypical Rates

Runway	FAF State	Atypical per 1,000	n (flights)
18C	FAF_HIGH	311	4,767
18C	FAF_ON_ALT	113	12,305
18C	FAF_LOW	277	413
18R	FAF_HIGH	507	8,788
18R	FAF_ON_ALT	187	627
18R	FAF_LOW	47	645

For runway 18C, aircraft classified as FAF_HIGH exhibit a slightly higher rate of atypical behaviour than FAF_LOW aircraft. As summarised in Table 10, FAF_HIGH aircraft show 311 atypical approaches per 1,000, compared with 277 per 1,000 for FAF_LOW aircraft, corresponding to a difference of 34 atypical approaches per 1,000. While this indicates that vertical state at the FAF is associated with atypical behaviour on runway 18C, the magnitude of the difference is limited, and the conditional rates alone do not indicate whether this association originates at the FAF itself or is established earlier in the arrival.

In contrast, runway 18R displays a markedly stronger association between FAF vertical state and atypical behaviour. Aircraft crossing the FAF above the nominal altitude exhibit 507 atypical approaches per 1,000, whereas FAF_LOW aircraft show only 47 atypical approaches per 1,000, yielding a difference of approximately 460 atypical approaches per 1,000. This pronounced contrast demonstrates that, for runway 18R, elevated vertical energy at the FAF is closely associated with the occurrence of atypical energy dissipation during the subsequent final approach segment.

Importantly, these conditional rates describe the outcome at the FAF, but do not in themselves explain how the observed vertical states are established. To determine whether the FAF vertical state reflects conditions already present upstream in the arrival, the following section examines the role of arrival streams, upstream waypoint vertical state, and late-stage instability prior to crossing the FAF.

4.4 Upstream Effects to Vertical Deviation and Atypical Outcomes

Building on the runway-dependent relationship between FAF vertical state and atypical approach behaviour identified in Section 4.3, this section examines whether upstream vertical conditions contribute to the development of elevated vertical energy at the FAF. The analysis focuses on two potential contributors: arrival stream composition and vertical state at key upstream waypoints.

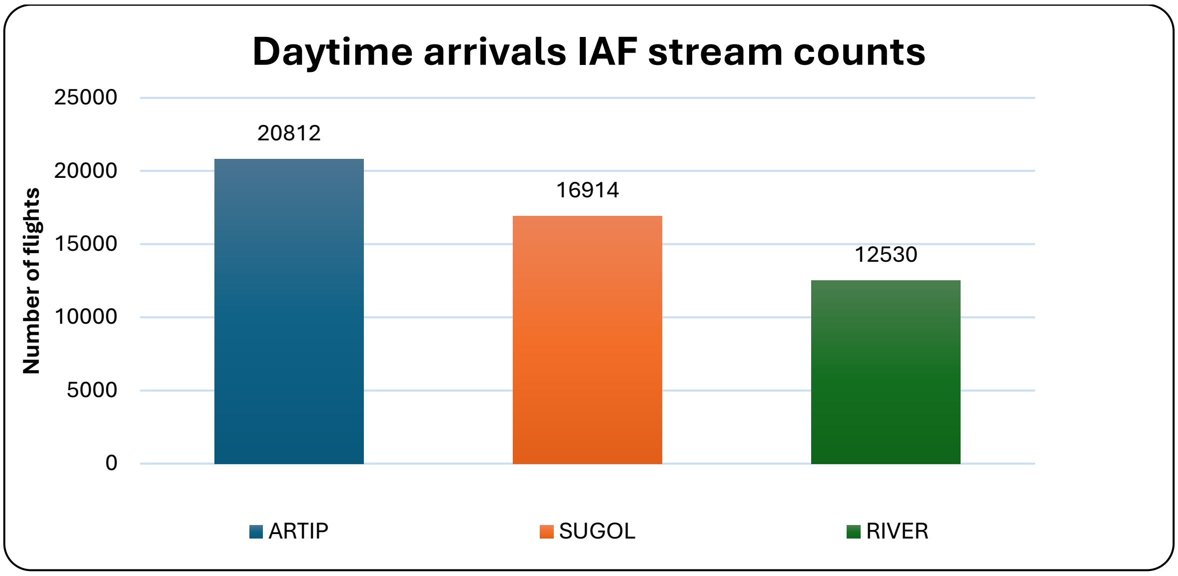


Figure 15 Daytime arrivals IAF stream counts

Figure 14 illustrates the daytime distribution of arrivals across the three Initial Approach Fixes (IAFs): ARTIP, RIVER, and SUGOL. Each stream is sufficiently represented, ensuring that differences observed are not driven by limited sample sizes.

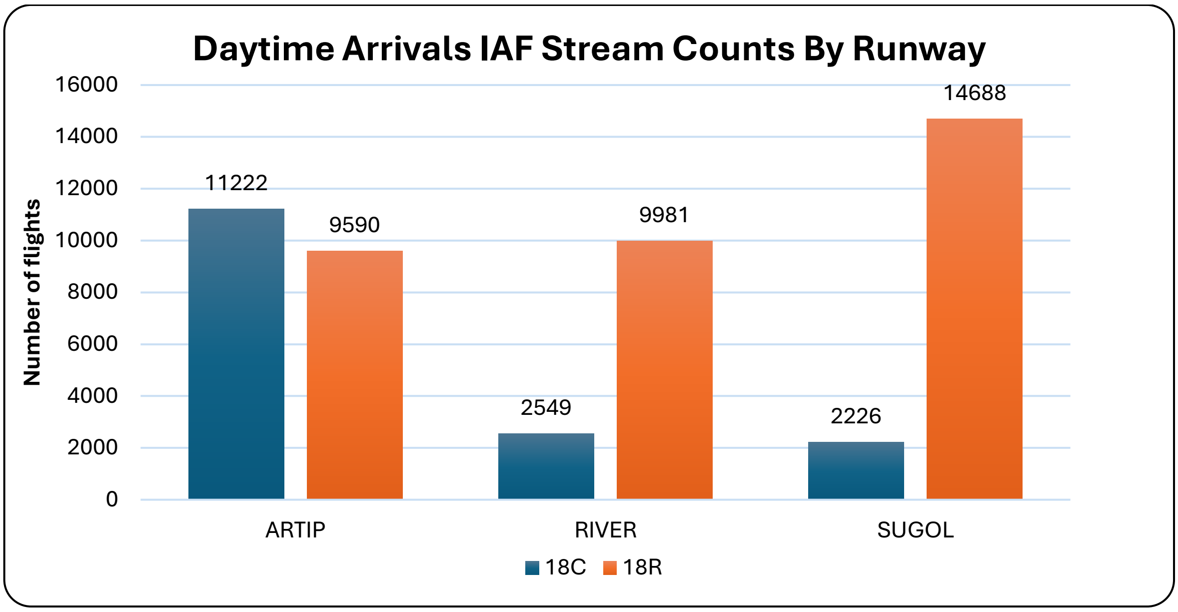


Figure 16 Daytime Arrivals IAF Stream Counts By Runway

These differences in stream composition are relevant, as they influence the vertical geometry and energy-management context in which aircraft approach the FAF.

To assess whether vertical deviations observed at the FAF are already established upstream, the aircraft's vertical state was evaluated at key waypoints along the arrival path. For runway 18C, the waypoints **ALINA** and **SIDNI** were selected, as illustrated in Figure 17 marked red.

Rather than considering upstream waypoints in isolation, the analysis first examines how vertical state evolves between ALINA and SIDNI, and subsequently evaluates whether specific upstream states or state transitions are associated with atypical outcomes at the FAF.

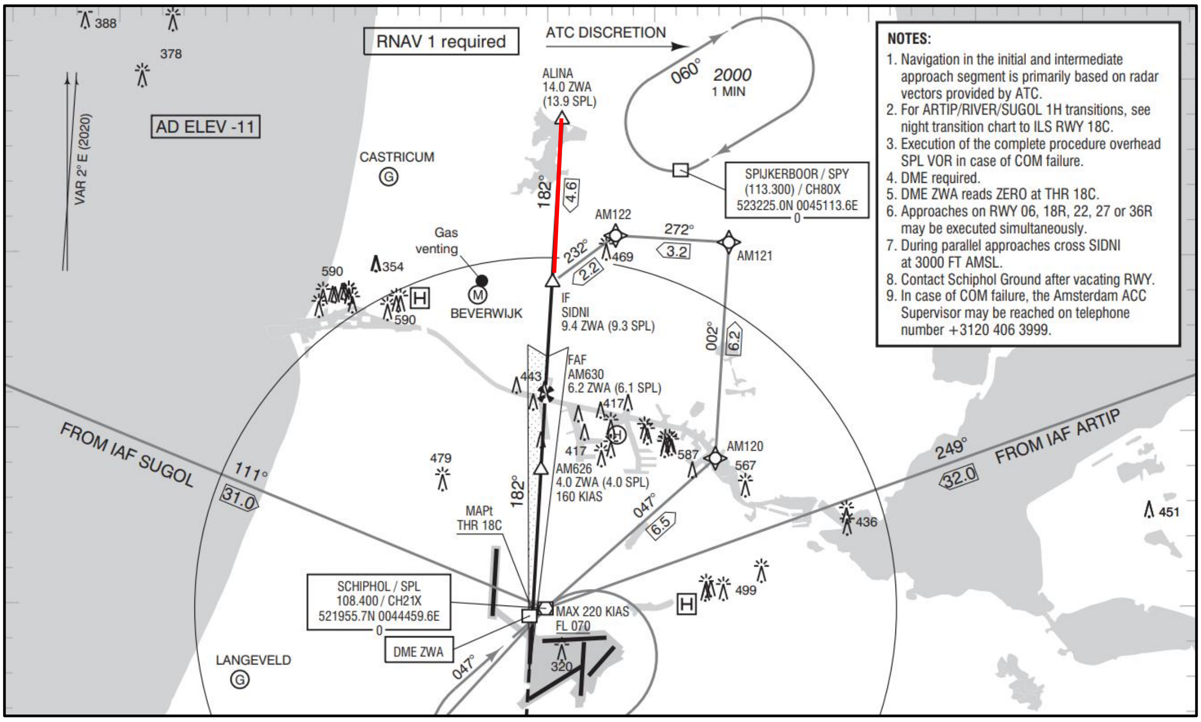


Figure 17 ILS 18C Chart

The reference height is taken directly from the published ILS runway 18C chart. The circled annotation in Figure 18 specifies the nominal altitude constraint associated with the intermediate approach segment at this location, which represents the intended vertical state from which the aircraft should transition towards the FAF and intercept the glideslope in a stabilised manner.

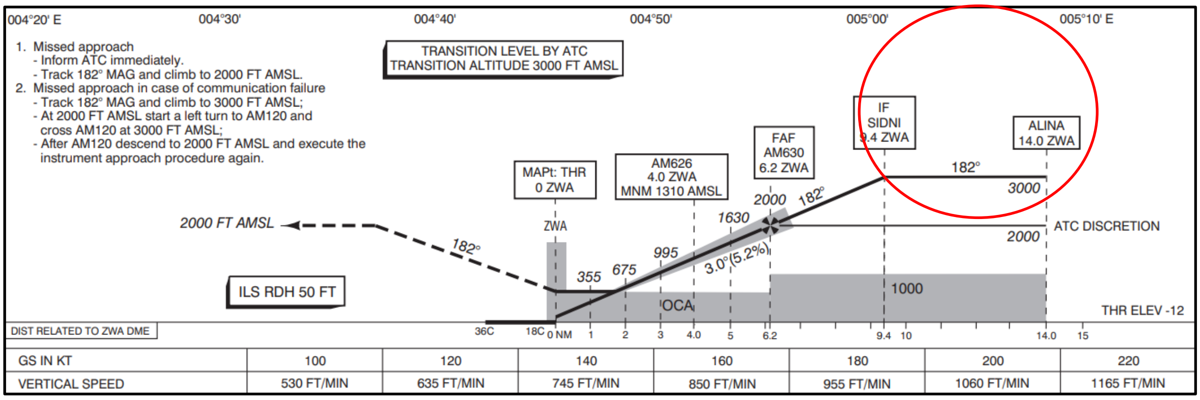


Figure 18 ILS 18C Height Prescription

Table 10 presents the transition matrix between ALINA and SIDNI, expressed as row-wise percentages. Each row represents the vertical state at ALINA, while each column indicates the corresponding vertical state at SIDNI.

Table 10 SIDNI to ALINA

ALINA	SIDNI LOW	SIDNI ON	SIDNI HIGH
ALINA LOW	54.96%	1.94%	43.10%
ALINA ON	6.53%	14.57%	78.90%
ALINA HIGH	7.39%	29.53%	63.08%

The table shows that the vertical state is not static along the arrival. While a majority of ALINA_LOW aircraft remain low at SIDNI, a substantial proportion transitions to higher states. Similarly, although most ALINA_HIGH aircraft remain high at SIDNI, nearly one-third correct to SIDNI_ON and a smaller fraction correct to SIDNI_LOW. This explains why the number of SIDNI_HIGH aircraft is lower than the number initially classified as ALINA_HIGH and confirms that meaningful vertical corrections frequently occur between the two waypoints.

Table 11 links these upstream vertical-state transitions to atypical outcomes at the FAF. For each ALINA–SIDNI combination, the table reports the total number of flights and the number that subsequently exhibited atypical behaviour.

Table 11 Atypical Rates from Waypoints ALINA and SIDNI

ALINA to SIDNI	SIDNI LOW	SIDNI ON	SIDNI HIGH
LOW	227	8	178
Atypical at FAF	6	0	8
ON	69	154	834
Atypical at FAF	2	6	37
HIGH	999	3,991	8,524
Atypical at FAF	27	149	375

Across all ALINA states, no consistent relationship is observed between vertical state at ALINA alone and atypical behaviour at the FAF. Aircraft classified as ALINA_HIGH that subsequently correct to SIDNI_LOW exhibit atypical rates comparable to aircraft that were never high upstream. Conversely, aircraft that remain SIDNI_HIGH, regardless of their vertical state at ALINA, consistently show the highest atypical rates.

This pattern indicates that persistence of elevated vertical energy closer to the FAF, rather than being high at ALINA per se, is the primary driver of atypical approach behaviour on runway 18C. Vertical deviations observed earlier in the arrival are not inherently problematic if they are corrected before SIDNI, whereas deviations that persist into the intermediate approach segment are increasingly associated with aggressive energy dissipation downstream.

A clearer relationship emerges when the vertical state is evaluated at SIDNI rather than ALINA. Atypical rates increase from 26.6 per 1,000 for SIDNI_LOW aircraft, to 37.4 per 1,000 for SIDNI_ON, and 44.0 per 1,000 for SIDNI_HIGH aircraft. This monotonic increase indicates that the vertical state closer to the FAF is more strongly associated with subsequent energy-management challenges, consistent with the reduced remaining distance available for stabilisation.

Taken together, these findings indicate that for runway 18C, upstream vertical deviations only become operationally meaningful when they persist into the later stages of the arrival. While vertical state at ALINA alone shows limited association with atypical outcomes, deviations that remain present at SIDNI are increasingly likely to propagate downstream and contribute to atypical energy-loss behaviour in the final approach segment.

To complement the analysis performed for runway 18C, the relationship between upstream vertical state and the occurrence of atypical energy-loss behaviour was also evaluated for runway 18R. Aircraft were classified based on their altitude relative to expected vertical constraints at two upstream reference points: PEVOS (9.4 NM from threshold, nominal constraint 2,000 ft) and DIBRU (13.0 NM from threshold, assumed constraint 3,000 ft). These reference constraints are taken from the published ILS runway 18R chart and are highlighted in red in Figure 19. Using an along-track gate-based approach, these reference points were evaluated without requiring an exact waypoint crossing, thereby increasing robustness against track dispersion and radar sampling effects.

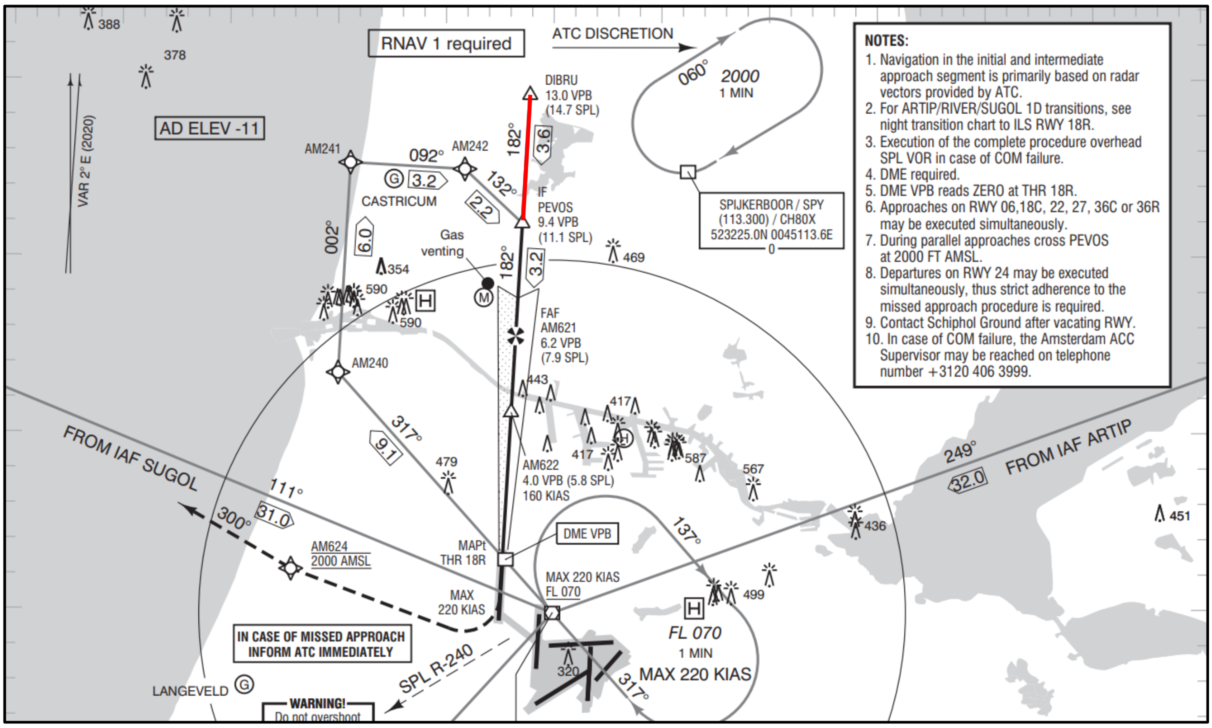
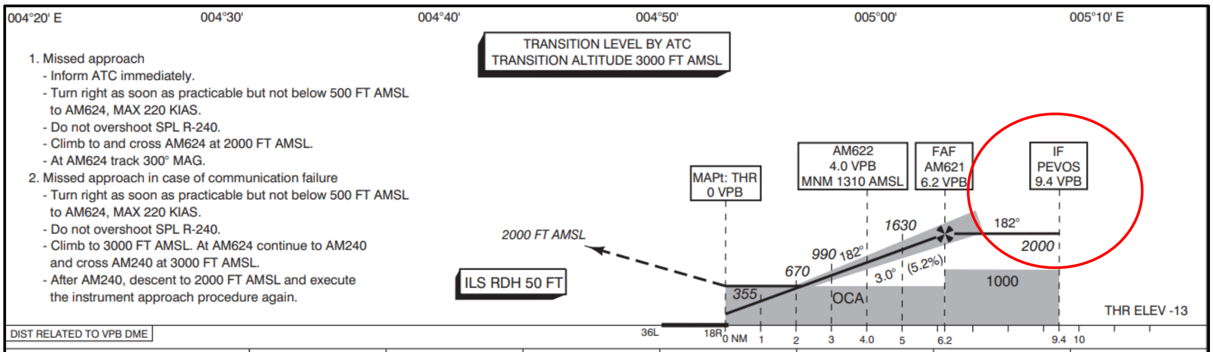


Figure 19 ILS 18R Chart

The reference height is taken directly from the published ILS runway 18C chart. The circled annotation in Figure 20 specifies the nominal altitude constraint associated with the intermediate approach segment at this location, which represents the intended vertical state from which the aircraft should transition towards the FAF and intercept the glideslope in a stabilised manner.



GS IN KT	100	120	140	160	180	200	220
VERTICAL SPEED	530 FT/MIN	635 FT/MIN	745 FT/MIN	850 FT/MIN	955 FT/MIN	1060 FT/MIN	1165 FT/MIN

Figure 20 ILS 18C Height Prescription

Atypical behaviour was defined based on the average loss of airspeed per nautical mile between the FAF (6.2 NM) and the 3 NM point on final approach. Aircraft exhibiting a speed reduction exceeding 20 kt per NM over this segment were classified as atypical. To ensure stable estimation, median speeds were extracted at both endpoints using the nearest available observations within a predefined tolerance band. In total, 17,908 approaches to runway 18R were retained for analysis after applying geometric, kinematic, and data-quality filters.

Tables 12 and 13 summarise the proportion of atypical approaches conditional on the vertical state at PEVOS. Aircraft classified as LOW at PEVOS exhibited an atypical rate of 32.7% (327 per 1,000 approaches), compared to 32.5% for aircraft classified as HIGH. Aircraft that were ON the nominal constraint showed a lower atypical rate of 27.8%, although this category contained relatively few observations.

Overall, these results indicate no substantial difference in atypical behaviour between aircraft that are high or low at PEVOS. While being on the expected altitude appears marginally favourable, the limited sample size prevents firm conclusions for this category.

A similar pattern is observed at DIBRU. Aircraft classified as LOW at DIBRU experienced an atypical rate of 33.3%, compared to 32.6% for HIGH aircraft. Approaches classified as ON the assumed 3000 ft constraint displayed a lower atypical rate of 27.6%, consistent with the findings at PEVOS.

Again, the difference between HIGH and LOW vertical states is minimal, suggesting that deviations above or below the nominal altitude at DIBRU do not materially affect the likelihood of atypical energy-loss behaviour later in the approach.

Table 12 DIBRU to PEVOS

PEVOS	DIBRU LOW	DIBRU ON	DIBRU HIGH
PEVOS LOW	51.20%	7.40%	41.40%
PEVOS ON	33.30%	30.60%	36.10%
PEVOS HIGH	42.60%	9.70%	47.70%

Table 13 Atypical Rates from Waypoints DIBRU and PEVOS

DIBRU to PEVOS	DIBRU LOW	DIBRU ON	SIDNI HIGH
LOW Atypical at FAF	7,148 2,394	1,035 284	3,772 1,232
ON Atypical at FAF	20 3	2 1	12 6
HIGH Atypical at FAF	2,013 663	279 78	3,598 1,168

The joint distribution of vertical states at PEVOS and DIBRU shows that aircraft generally retain their relative vertical state between the two fixes, with ON–ON combinations being comparatively rare. The joint atypical-count table further demonstrates that atypical occurrences scale largely with traffic volume across the different combinations, without any single vertical-state pairing exhibiting a disproportionately high number of atypical approaches.

Across both upstream reference points, the results for runway 18R demonstrate that vertical state alone is a weak predictor of atypical energy-loss behaviour between the FAF and 3 NM. Although aircraft that are closer to the expected vertical profile tend to show slightly lower atypical rates, the overall differences remain modest. This suggests that other factors—such as speed control strategies, aircraft type, wind conditions, or late tactical interventions—likely play a more dominant role in determining approach stability.

Importantly, the atypical rates observed for runway 18R (approximately 32–33%) are higher in absolute terms than those found for runway 18C. This indicates that runway-specific or procedural characteristics may influence energy management behaviour and warrants further investigation when comparing approach performance across runways.

5. Conclusion

The objective of this thesis was to determine whether variations between the intended arrival procedure design and actual flown trajectories toward the Final Approach Fix (FAF) at Amsterdam Airport Schiphol are associated with atypical approach behaviour for runways 18R and 18C. In this thesis, approach behaviour was assessed using two complementary measures: (i) stability-related exceedances at the FAF (vertical speed, airspeed, bank angle, and ILS dot-equivalent deviations), and (ii) an "atypical" energy-management outcome defined by unusually high airspeed reduction between the FAF and the 3 NM stabilisation point.

The main research question of this thesis is as follows:

"To what extent are atypical energy-loss events after the FAF and stability-related exceedances at the FAF for runways 18R and 18C associated with published arrival procedure design characteristics and upstream vertical states, as observed in operational trajectory data?"

Compliance with the published night transitions

The compliance assessment of the published night transitions from ARTIP, RIVER, and SUGOL shows that the routes to both runways 18R and 18C satisfy ICAO PANS-OPS vertical design limits. The theoretical descent gradients for the Initial Approach Segment (IAF to NIRSI) remain within the maximum limits, and the Intermediate Segment gradients from NIRSI toward the respective FAFs also remain below the applicable maximum values. Although the SUGOL transition requires a higher descent demand than ARTIP and RIVER due to its shorter track distance, it remains within the allowable design envelope. These results establish that the published night arrival procedures are compliant by design and provide a formal baseline for interpreting operational behaviour.

Night-time FAF behaviour

The night-time operational analysis evaluated aircraft state at the FAF using vertical speed, airspeed, bank angle, and ILS tracking performance. The results show that parameter exceedances occurred only in an isolated manner and did not co-occur in combinations that would indicate broader instability. Lateral localiser tracking remained tightly clustered, and while runway 18R exhibited a wider spread in vertical ILS deviation than runway 18C, correlation analysis did not show meaningful coupling between vertical deviation and airspeed, vertical speed, or bank angle at the FAF. Overall, the nighttime results do not indicate that the published night transition routes systematically induce unstable behaviour at the FAF; instead, observed variability is more consistent with benign operational dispersion and runway-specific sensitivity to upstream conditions.

Daytime "atypical" behaviour and the role of FAF vertical state

During daytime operations, a markedly different picture emerges due to higher traffic volumes and a substantially larger dataset. The analysis confirms that runway 18R and 18C differ in how strongly FAF vertical state is associated with downstream atypical energy-loss behaviour (FAF to 3 NM). For runway 18R, aircraft arriving high at the FAF show a substantially higher probability of atypical energy dissipation, while aircraft arriving low show very low atypical rates. This indicates that, for runway 18R, the vertical energy state at the FAF is a dominant discriminator for whether sharp energy corrections occur after the FAF.

For runway 18C, the relationship between FAF vertical state and atypical energy-loss behaviour is weaker and less separating: aircraft classified as high and low at the FAF display comparatively similar atypical rates. This suggests that for runway 18C, atypical behaviour in the final approach segment is not explained primarily by the instantaneous FAF vertical state alone, but is more likely linked to how energy is managed and corrected across a broader portion of the arrival and intermediate segment.

Importantly, the distribution of vertical-state categories at the FAF is similar across the two runways. Therefore, the runway-dependent differences in atypical outcomes are not explained by one runway simply receiving more “high” arrivals at the FAF; rather, they reflect a different relationship between vertical setup at the FAF and the need for downstream energy correction.

Upstream vertical state: persistence matters (18C) and “state alone” is weak (18R)

The upstream analysis for runway 18C demonstrates that vertical deviations earlier in the arrival are not inherently problematic if they are corrected before later fixes. The transition analysis between ALINA and SIDNI shows that vertical state changes substantially along the route, and the strongest association with atypical outcomes is observed when the elevated vertical state persists closer to the FAF (i.e., at SIDNI). In other words, being high far upstream is not decisive by itself; remaining high into the later intermediate approach portion is what corresponds most clearly with atypical downstream energy-loss behaviour.

For runway 18R, the gate-based assessment at DIBRU and PEVOS indicates that being high or low at these upstream reference points produces only modest differences in atypical rates. This implies that upstream vertical state alone (at the analysed waypoints) is a weak predictor of atypical energy loss after the FAF. Taken together with the strong FAF-state relationship found for runway 18R, this supports the interpretation that the most operationally relevant divergence for runway 18R is established relatively late, close to the FAF, rather than being consistently “locked in” far upstream as a simple high/low condition at DIBRU or PEVOS.

Answer to the main research question

Overall, the results show that published procedure design compliance is not, by itself, sufficient to explain atypical approach behaviour, and there is no evidence that non-compliance or inherently excessive design gradients are responsible for atypical outcomes. Instead, atypical behaviour (as defined by unusually high energy dissipation between the FAF and 3 NM) is runway dependent and relates primarily to how vertical energy states develop and persist as aircraft approach the FAF.

- For night-time operations, the published transitions are compliant and operational behaviour at the FAF does not exhibit systematic instability patterns attributable to the route design.
- For daytime operations, atypical outcomes occur in a runway-dependent way: runway 18R shows a strong dependence on FAF vertical state, while runway 18C shows a weaker dependence on FAF state and a clearer role of upstream persistence closer to the FAF (e.g., at SIDNI).

Therefore, atypical approach behaviour at Schiphol is best interpreted as an outcome of the interaction between arrival geometry, the evolution of vertical energy state toward the FAF, and the remaining distance available for stabilisation, rather than a direct consequence of non-compliant published procedure design.

5.1 Recommendations

The analyses indicate that the published procedures are compliant by design and that night-time operations do not show systematic instability patterns at the FAF. Daytime results, however, reveal runway-dependent differences in how vertical energy state develops toward the FAF and how strongly this relates to atypical energy dissipation between the FAF and 3 NM. The following recommendations, therefore, focus on improving predictability and consistency of approach set-up, rather than addressing a demonstrated safety deficiency.

1. **Strengthen vertical profile management on the 18C arrival streams, with emphasis on persistence close to the FAF**

   For runway 18C, atypical energy-loss behaviour is not strongly explained by being high at a single early fix alone; instead, the results indicate that an elevated vertical state becomes operationally meaningful when it persists into the later intermediate portion (e.g., closer to SIDNI). Operational review should therefore focus on supporting earlier correction of "high" states so that aircraft are established closer to the intended vertical profile before entering the final approach segment. This can be addressed through clearer vertical planning expectations for crews and by reviewing whether arrival stream management encourages timely descent execution, thereby reducing the likelihood of late energy corrections downstream.

2. **Prioritise avoiding "high at the FAF" conditions on runway 18R to reduce downstream atypical energy corrections**

   For runway 18R, the relationship between FAF vertical state and atypical energy-loss events after the FAF is strong: approaches that arrive high at the FAF are substantially more likely to exhibit sharp energy dissipation between the FAF and 3 NM. Operational attention should therefore be directed toward measures that reduce the frequency of high FAF crossings on 18R (for example, by reinforcing consistent vertical set-up in the final part of the intermediate segment and ensuring timely stabilisation onto the nominal descent profile). While upstream high/low states at the selected gates show only modest predictive value, the results suggest that preventing late development or persistence of high vertical energy approaching the FAF is the most effective lever for improving predictability on 18R.

3. **Adopt a runway-specific monitoring metric that links FAF vertical state to post-FAF energy management**

   Given that the key operational discriminator in the results is the combination of (i) FAF vertical state and (ii) energy-loss behaviour between the FAF and 3 NM, it is recommended to implement a simple monitoring view that tracks these two measures together by runway and arrival stream. This would enable routine identification of when elevated FAF crossings translate into late corrections (particularly on 18R) and would support targeted operational follow-up (e.g., by time of day, traffic mix, or stream composition) without requiring attribution to ATC actions within this thesis.

4. **Analyse vertical-profile behaviour in the context of operational constraints, including noise procedures**

   Although nighttime results show no systematic instability at the FAF, operational constraints such as noise-abatement procedures can influence descent planning and energy management strategies. It is recommended that any operational review of vertical deviations and late corrections explicitly considers the role of noise-related constraints and procedural objectives. This helps distinguish deviations that reflect intentional operational strategy from those that represent avoidable variability and supports balanced optimisation between noise objectives and approach predictability.

5.2 Future Work

Building on the findings of this thesis, several directions are recommended for future research to strengthen causal interpretation and test the generalisability of the observed runway-dependent patterns:

1. **Extend the analysis to additional runways and arrival configurations**

   This thesis focused on runways 18R and 18C under the investigated arrival structure. Future work should repeat the same FAF-based stability and post-FAF energy-loss analyses for other Schiphol runways and configurations (including different runway modes and transition structures). This would determine whether the strong runway dependence observed here is specific to 18R/18C geometry or reflects a broader, system-level phenomenon.

2. **Integrate meteorological drivers, especially wind**

   Meteorological conditions were not explicitly modelled in this thesis. Future research could merge trajectory data with wind observations or model data (e.g., METAR/TAF, local wind sensors, or numerical weather products) to quantify the effect of headwind/tailwind components, crosswind, gustiness, and vertical wind gradients on (i) vertical deviation at the FAF and (ii) late-stage energy dissipation between the FAF and 3 NM. This would help separate effects attributable to procedure geometry from those driven by environmental variability.

3. **Incorporate tactical ATC interventions and operational constraints**

   Although this thesis characterises operational behaviour through observed trajectories, it does not explicitly include tactical ATC actions such as vectoring, speed control, late descent clearances, or compressions due to sequencing. Future work could combine trajectory data with ATC instruction logs (where available) or infer tactical interventions from track dispersion and speed-control patterns to assess how these decisions contribute to elevated vertical states at the FAF and to subsequent energy-loss behaviour.

4. **Assess temporal robustness through multi-year and seasonal analysis**

   The analysed dataset covers 1 January 2025 to 28 June 2025. Extending the study to longer periods would allow testing whether the identified relationships (e.g., the strong dependence of atypical outcomes on FAF vertical state for runway 18R) remain stable across seasons, varying traffic demand, and operational changes. A longitudinal approach would also help identify trends, regime shifts, or the impact of procedural updates.

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Appendix A – Reflection

Upon concluding this thesis, I reflect on the past intensive and meaningful months of research that shaped this dissertation. The topic proved challenging from the outset, particularly due to the limited availability of reference literature directly addressing atypical approach behaviour within the specific operational and procedural context studied. Developing a clear understanding of what constitutes an atypical approach, and subsequently relating this concept to established notions such as non-stabilised approaches, go-arounds, and procedural compliance, required both independent exploration and continuous refinement of the research focus.

As the research progressed, the complexity of the subject became increasingly apparent. What initially appeared to be a relatively narrow question evolved into a broader investigation of how procedure design, operational practices, and aircraft energy management interact during the arrival phase. Translating these concepts into measurable parameters using surveillance data was a demanding but rewarding process. It required careful methodological choices to ensure that the analysis remained both technically sound and operationally meaningful.

I would like to express my sincere gratitude to Koos for giving me the opportunity to conduct this research at LVNL and for his trust and support throughout the process. His guidance, availability for discussion, and willingness to challenge assumptions played a key role in shaping both the direction and depth of this thesis. The opportunity to work on a topic of direct operational relevance within LVNL was invaluable and greatly enriched the learning experience.

In addition, I would like to thank the many colleagues within LVNL who generously shared their thoughts, insights, and expertise on this topic. Their practical perspectives helped ground the research in operational reality and provided essential context for interpreting the analytical results. The openness with which ideas were exchanged contributed significantly to the quality and relevance of this work.

From a technical perspective, this thesis significantly strengthened my analytical and programming skills. Working with large volumes of VEMMIS trajectory data required efficient data handling, structured coding, and iterative debugging in Python. Although the extent of programming involved exceeded my initial expectations, it became one of the most valuable aspects of the project. Over time, I developed a much stronger understanding of data processing, geometric analysis, and performance optimisation, skills that I consider highly relevant for my future career in the aviation domain.

Equally important was the development of my academic writing and critical reasoning skills. Structuring a complex analysis into a coherent narrative, clearly separating methodology, results, and interpretation, and ensuring consistency throughout the thesis required sustained effort. The iterative writing process improved my ability to communicate technical findings in a precise and structured manner.

Looking back, this thesis has been both challenging and rewarding. It not only deepened my understanding of arrival procedure design and operational behaviour but also strengthened my confidence in conducting independent, data-driven research. I am grateful for the opportunity to have worked on a topic with direct relevance to real-world aviation operations and for the support of everyone at LVNL who contributed to this work in their own way.