

Trajectory-Based Operations in Mixed Datalink Equipage Conditions

Trajectory Management Evolution in Amsterdam
ACC

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Thesis Report

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Preface

This thesis marks the completion of my Master's degree in Aerospace Engineering at Delft University of Technology. The research was carried out at Luchtverkeersleiding Nederland, within the Knowledge and Development Centre, and was supervised by Ferdinand Dijkstra, Joost Ellerbroek, and Bob van Dillen.

The past ten months have formed one of the most insightful and steepest learning curves of my academic journey. This project has taught me a great deal about myself, about the world of research, and about the fascinating field of air traffic management. I am very grateful for the opportunity to have worked on a topic that has challenged me, motivated me, and deepened my interest in aviation.

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Finally, I would like to thank my family, friends, and loved ones for their support during this journey. I am grateful for the interest you have shown in my work, for giving me the opportunity to talk about my research, and for allowing me to share my excitement about it.

This journey marks the end of my academic time at Delft University of Technology. It has been a period in which I had the opportunity to develop myself in many ways, meet many interesting people, discover my passion for aviation, and connect with people from all over the world. I am grateful for all the opportunities I have had during this period, and I look forward to what the future will bring.

*Niels Prins
Schiphol-Oost, June 2026*

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Nomenclature

4D Four-Dimensional	FMS Flight Management System
AAA Amsterdam Advanced ATC	FPA Flight Path Angle
ACARS Aircraft Communications Addressing and Reporting System	HF High Frequency
ACC Area Control Centre	IAF Initial Approach Fix
ADS-B Automatic Dependent Surveillance–Broadcast	ICAO International Civil Aviation Organization
ADS-C Automatic Dependent Surveillance–Contract	IPI Intermediate Projected Intent
ANSP Air Navigation Service Provider	ISA International Standard Atmosphere
APP Approach Control	KPI Key Performance Indicator
ATC Air Traffic Control	LVNL Luchtverkeersleiding Nederland
ATM Air Traffic Management	MUAC Maastricht Upper Area Control
ATN Aeronautical Telecommunication Network	NextGen Next Generation Air Transportation System
ATN B1 Aeronautical Telecommunication Network Baseline 1	PCE Polynomial Chaos Expansions
ATS Aeronautical Telecommunication Services	ROCD Rate of Climb/Descent
ATSU Air Traffic Service Unit	RTA Required Time of Arrival
ATS B2 Aeronautical Telecommunication Services Baseline 2	SARA Speed and Route Advisor
BADA Base of Aircraft Data	SES Single European Sky
CAS Calibrated Airspeed	SESAR Single European Sky ATM Research
CD&R Conflict Detection & Resolution	SID Standard Instrument Departure
CPDLC Controller–Pilot Data Link Communications	SOCP Second–Order Cone Programming
CTA Control Area	STAR Standard Arrival Route
CToA Constrained Time of Arrival	STP Space–Time Prism
CTR Control Region	STPCS Space–Time Potential Conflict Space
DoF Degrees of Freedom	SWIM System Wide Information Management
EAT Expected Approach Time	TAS True Airspeed
EPP Extended Projected Profile	TBO Trajectory-Based Operations
FANS Future Air Navigation System	TCP Trajectory Change Point
FIR Flight Information Region	TMA Terminal Maneuvering Area
	ToD Top of Descent
	UTA Upper Control Area
	VHF Very High Frequency
	WGS World Geodetic System

General Introduction

The continuous increase in air traffic demand across Europe places growing pressure on the capacity, efficiency, and predictability of current Air Traffic Management (ATM) systems. Geopolitical developments and the emergence of new airspace users, such as unmanned aircraft and high-altitude aircraft, further increase the complexity of the operating environment. These developments challenge predominantly tactical and sector-based control, and motivate operational concepts that support earlier coordination and more systematic exchange of trajectory information. Trajectory-Based Operations (TBO) provides such a framework by using Four-Dimensional (4D) trajectories as the common reference for planning, monitoring, and coordination between air and ground systems.

The implementation of TBO depends on the availability of aircraft intent information and on communication means that can support trajectory updates. These capabilities are not uniform across the fleet. Schiphol traffic contains a heterogeneous mix of technological standards, such as Future Air Navigation System (FANS) 1/A, Aeronautical Telecommunication Network Baseline 1 (ATN B1), and Aeronautical Telecommunication Services Baseline 2 (ATS B2), which provide different levels of trajectory information and digital update capability.

During the transition towards more advanced TBO, mixed datalink equipage conditions will therefore remain operationally relevant. Some aircraft provide more detailed intent information and more integrated update capability than others. This heterogeneity affects the predictability of future trajectories and the extent to which trajectory changes can be planned and coordinated by a ground-based system.

This study evaluates how these mixed datalink capabilities affect trajectory management in Amsterdam Area Control Centre (ACC) airspace. A TBO concept is developed and tested using simulated inbound and outbound traffic, including fixed Flight Path Angle (FPA) arrival trajectories. A Monte Carlo experiment is used to test the concept under trajectory uncertainty, different traffic scenarios, and different fleet compositions that represent the transition towards more advanced datalink technology, with performance assessed in terms of safety and efficiency.

The thesis is structured in two parts. Part A contains the scientific article, which forms the final research contribution and presents the methodology, results, and conclusions of the study. Part B contains the literature review and research definition from the initial phase of the thesis. It provides the operational, technical, and methodological background on which the article is based, and documents the original research questions and project plan.

Part A

Scientific Article

Trajectory-Based Operations in Mixed Datalink Equipage Conditions: a Trajectory Management Evolution in Amsterdam ACC

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Abstract—Trajectory-Based Operations (TBO) are intended to improve Air Traffic Management (ATM) by enabling earlier planning, more consistent trajectory prediction, and reduced tactical conflict management. During the transition towards advanced Automatic Dependent Surveillance–Contract (ADS-C) and Controller–Pilot Data Link Communications (CPDLC) services, aircraft will provide different levels of downlinked intent and Flight Management System (FMS)-integrated trajectory update capability. This paper evaluates how this mixed datalink equipage affects a TBO concept for Amsterdam Area Control Centre (ACC) airspace. A strategic trajectory management model is developed for mixed inbound and outbound traffic between FL110 and FL260, combining fixed Flight Path Angle (FPA) descents with probabilistic Conflict Detection & Resolution (CD&R). Equipage-dependent uncertainty is represented through descent angle, target descent speed, and wind, while traffic density and fleet composition are varied in a Monte Carlo experiment. The results show that increasing equipage capability reduces trajectory adjustments and residual losses of separation, with the clearest benefits in higher density scenarios. Flown track distance and modelled work also decrease as more advanced equipage becomes available, although work reductions are small and occur mainly outside the Amsterdam ACC conflict management volume. Expected Approach Time (EAT) adherence remains broadly comparable across equipage compositions.

Index Terms—Air Traffic Management, Trajectory-Based Operations, ADS-C, CPDLC, Mixed Datalink, Probabilistic Conflict Detection and Resolution, Simulation

I. INTRODUCTION

Air Traffic Management (ATM) is facing increasing pressure from sustained growth in demand, rising operational complexity, and tighter environmental and airspace constraints [1]. These developments challenge predominantly tactical, sector-based control and motivate operational concepts that support earlier coordination and more predictive traffic management.

Trajectory-Based Operations (TBO) has been proposed to support this shift by enabling coordination based on shared trajectory information, with the aim of improving trajectory predictability and operational efficiency at both the sector and network level [2, 3]. The practical application of TBO is enabled by digital air–ground communication, most notably through Automatic Dependent Surveillance–Contract (ADS-C) and Controller–Pilot Data Link Communications (CPDLC). These technologies allow trajectory intent, constraints, and

clearances to be exchanged with greater structure than voice communication alone, while evolving standards such as Future Air Navigation System (FANS) 1/A and Aeronautical Telecommunication Services Baseline 2 (ATS B2) increase the level of integration between digital communication and the onboard Flight Management System (FMS).

Previous work has demonstrated several enabling elements of TBO. SESAR Joint Undertaking [4] and Guerreiro et al. [5] demonstrated digital trajectory exchange in realistic operational scenarios, while Jongen et al. [6] demonstrated decision support advisories for traffic flow management. More specifically, Gong et al. [7] evaluated a datalink-enabled TBO concept in a pilot and controller in the loop simulation under mixed datalink equipage, including conflict resolution advisories, tactical conflict detection, and weather avoidance rerouting. Buck et al. [8] developed representative 2040 TBO simulation scenarios using real-world route data, environmental constraints, ADS-C Extended Projected Profile (EPP), CPDLC, high-density traffic, and mixed advanced service and baseline equipage.

These studies establish the relevance of digital trajectory exchange, controller advisory support, and mixed equipage simulation. However, it remains unclear how differences in ADS-C and CPDLC capability within the same traffic environment affect trajectory management performance. This gap is relevant during incremental deployment, where aircraft differ in the intent information available to the ground system and in the extent to which trajectory updates can be integrated with the onboard FMS.

The main contribution of this paper is an evaluation of how mixed datalink equipage affects a TBO conflict management model in simulated Amsterdam Area Control Centre (ACC) sectors 1 and 2 between FL110 and FL260. The model considers mixed inbound and outbound traffic, fixed Flight Path Angle (FPA) arrivals, probabilistic Conflict Detection & Resolution (CD&R), and Monte Carlo sampling of wind field mismatch and arrival intent. By combining equipage-dependent predictor access with traffic load and fleet composition scenarios, the study quantifies how mixed equipage influences trajectory predictability, conflict management demand, and operational efficiency.

The remainder of this paper is structured as follows. Section II presents the operational and technical background. Section III introduces the TBO simulation model developed in this study. Section IV describes the experimental methodology. Results are presented in Section V, followed by discussion and conclusions in Sections VI and VII, respectively.

II. BACKGROUND

This section establishes the background required to model conflict management under mixed equipage TBO. It first introduces datalink capability and fixed FPA descent as the two operational elements used to define the trajectory representation. It then discusses trajectory uncertainty and links this representation to CD&R.

A. Trajectory-Based Operations and Datalink Capability

Trajectory management within a TBO concept relies on predicted Four-Dimensional (4D) aircraft trajectories for earlier planning, sequencing, and conflict management. In this context, datalink capability is central to the performance of the framework. It determines both the extent to which future aircraft intent is available to the ground system and the reliability with which trajectory changes can be communicated to and executed by the aircraft [2, 3].

Voice communication constrains both sides of this capability. It provides limited structured future intent to the ground system, while issued clearances remain non-machine-readable and may correspond to multiple trajectory interpretations. The realised trajectory can therefore depend on crew interpretation, execution timing, and onboard system logic [9, 10].

CPDLC can partly reduce this ambiguity through standardised digital messages, especially when clearances can be loaded into the onboard FMS. ADS-C addresses the complementary predictor access dimension by providing aircraft state information and, depending on the supported report groups, future trajectory intent [9, 11–13].

This study distinguishes three functional datalink equipage classes: FANS 1/A, Aeronautical Telecommunication Network Baseline 1 (ATN B1), and ATS B2. Under FANS 1/A, intent information can be provided through the Intermediate Projected Intent (IPI) group, which contains a limited set of up to ten projected Trajectory Change Points (TCPs) generated by the onboard FMS. Under ATS B2, the EPP provides a denser trajectory description with up to 128 TCPs. Because ATN B1 does not mandate FMS integration or downlinked trajectory intent, it is represented in this study as supporting CPDLC without these capabilities [2, 9, 12]. Table I summarises the capability assumptions used to define these classes.

Table I

DATALINK CAPABILITIES OF THE EQUIPAGE CLASSES CONSIDERED IN THIS STUDY.

	FANS 1/A	ATN B1	ATS B2
ADS-C intent	IPI, up to 10 TCPs	–	EPP, up to 128 TCPs
CPDLC integration	Integrated with FMS	Not mandated	Integrated with FMS

The coexistence of these equipage classes is operationally relevant in the Dutch Flight Information Region (FIR). For

Schiphol traffic, 2023 equipage estimates indicate that approximately 93% of flights were equipped with ATN B1, while around 53% supported FANS 1/A. By 2028, ATN B1 equipage is projected to remain dominant at approximately 95%, while ATS B2 adoption is expected to reach approximately 40%. Over the same period, FANS 1/A equipage for Schiphol traffic is projected to increase to approximately 91% [14]. These figures indicate that trajectory management for Schiphol-related traffic will remain mixed equipage during the transition toward more advanced TBO capabilities.

B. Fixed Flight Path Angle Descent

A trajectory predictor requires a consistent trajectory representation. This is particularly relevant for arrivals, where the vertical profile strongly affects Top of Descent (ToD) location, timing, and conflict geometry. A fixed FPA descent provides one way to prescribe this vertical geometry, as illustrated in Figure 1. It is a continuous descent in which the vertical path is defined by one or more ground-referenced FPAs, denoted by γ , and can be imposed through altitude constraints along the arrival route, referred to as fixed FPA gates [15]. The resulting vertical geometry is prescribed, rather than determined by an individual FMS profile based on aircraft performance, mass, weather, and operational restrictions [15].

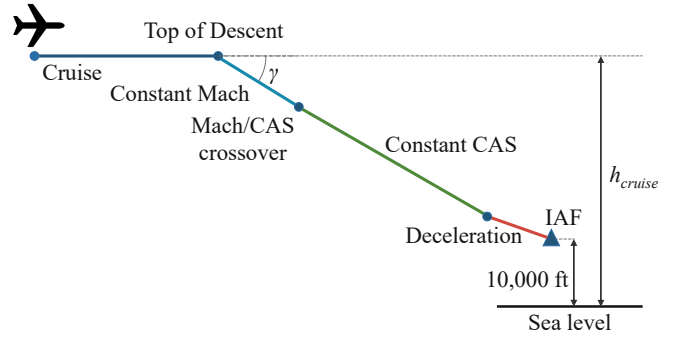


Figure 1. Fixed Flight Path Angle descent geometry.

Fixed FPA descent is relevant in this study because it provides a clear vertical structure for trajectory prediction and uncertainty representation. Under the conditions considered in the cited studies, fixed FPA descent can reduce vertical profile variability relative to less constrained descent profiles. This is particularly relevant in high density airspace, where a more predictable descent path can support earlier planning and reduce the need for additional separation margins or cancellation of the continuous descent [15, 16].

Speed control can be combined with fixed FPA descent to absorb arrival delay while maintaining the prescribed vertical path. In uncongested conditions, an idle FMS profile descent may remain more fuel efficient. However, when delay must be absorbed, fixed FPA descent may reduce the need for vectoring or level segments, which can improve fuel performance in congested operations [15, 16].

An FPA descent profile typically contains a constant Mach segment, a constant Calibrated Airspeed (CAS) segment below the crossover altitude, and deceleration segments near the

terminal area, as shown in Figure 1. The Mach/CAS crossover altitude is the altitude at which the True Airspeed (TAS) associated with the selected CAS equals the TAS associated with the descent Mach number. These phases can be represented using multiple FPA segments and shallow deceleration segments constrained by altitude restrictions [15]. Variation in the target descent CAS changes the ground speed profile and therefore affects the along-track evolution of the arrival trajectory. Since the vertical path is constrained by the prescribed descent angle, this along-track evolution also affects the altitude reached at a given prediction time.

C. Trajectory Uncertainty

Conflict management depends on the predicted future position of each aircraft. Fixed FPA descent provides a structured vertical path, but it does not remove uncertainty in timing, speed evolution, wind response, or aircraft intent. This subsection introduces the error metrics and uncertainty sources relevant to an equipage-dependent uncertainty model.

1) *Metrics*: Trajectory uncertainty is commonly characterised by the error between the predicted trajectory and the realised flight path [17, 18]. As illustrated in Figure 2, this error can be decomposed in a trajectory-aligned reference frame into along-track error, cross-track error, and vertical error. Along-track error is measured in the direction of the intended path and is closely related to timing error. Cross-track error is measured perpendicular to the intended path and represents lateral deviation. Vertical error represents the altitude deviation from the predicted profile. These same three components are later used as the axes of the trajectory-aligned covariance representation in the conflict detection model.

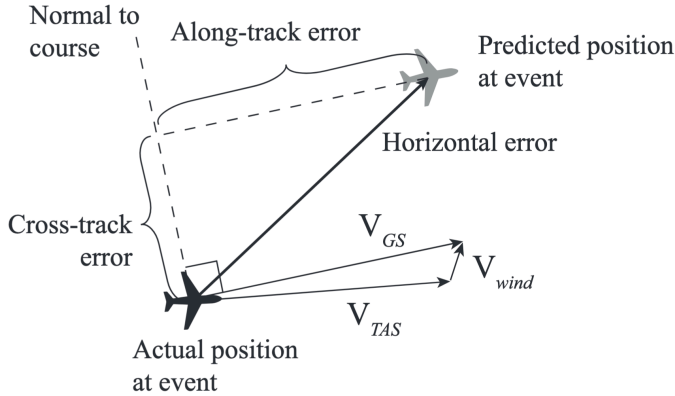


Figure 2. Track error divided into along-track and cross-track error [19].

Temporal error can be expressed as the difference between the predicted and realised time at a given location, or equivalently through the along-track displacement at a given time. This relation makes the along-track component particularly relevant for conflict management, arrival sequencing, and metering, because it affects both predicted conflict timing and arrival time adherence. For arrival metering, one key concern is whether the aircraft reaches a constraint point at the intended time [17, 20].

2) *Sources of uncertainty*: Trajectory prediction uncertainty arises from several sources, including aircraft intent, aircraft model and initial state errors, atmospheric conditions, and flight technical errors. Their relative importance depends on the flight phase, trajectory type, look-ahead time, and predictor inputs. Arrival intent and wind uncertainty are particularly relevant in this context, because both directly affect the future aircraft position on which conflict management depends.

a) *Aircraft intent*: Intent uncertainty arises when future control actions governing aircraft motion are unknown or only partially observable to the trajectory predictor [11, 21]. For arrival trajectories, unavailable route, altitude, speed, timing constraints, and transition points can affect both vertical and lateral track evolution. Unobservable parameters such as thrust setting, cost index, and target Indicated Airspeed (IAS) can influence Rate of Climb/Descent (ROCD) behaviour, speed evolution, and trajectory timing [22, 23]. Communication and execution differences can also shift key trajectory events, such as the ToD, through variations in pilot response time, automation logic, manual entry, and transition profile interpretation [11, 23].

b) *Atmospheric conditions*: Atmospheric uncertainty affects trajectory prediction through errors in temperature, pressure, and wind. Temperature and pressure errors influence airspeed conversions between TAS, CAS, and Mach number, but usually have a limited effect on trajectory prediction accuracy [21]. Wind is more influential because wind forecast errors directly affect aircraft motion relative to the ground [17, 24, 25]. Headwind and tailwind errors change the along-track component of ground speed, causing timing and position errors to accumulate along the trajectory, while crosswind errors mainly affect the relation between heading and track. Wind errors can also influence vertical tracking during climb and descent, because deviations in the wind field alter the energy and path evolution required to follow the intended vertical profile [26, 27].

These effects remain difficult to eliminate because wind information is available only at discrete altitude levels and limited temporal resolution. Fine-scale variations and forecast errors therefore remain unresolved and cause deviations between predicted and realised trajectories [28]. Prediction consistency can also be affected when the wind information available to the ground predictor differs from the information used by the flight crew or FMS [13]. Previous work has shown that the resulting wind-related trajectory prediction uncertainty depends on flight phase, trajectory type, and modelling assumptions, including for inbound idle and fixed FPA descents [21, 26, 27].

c) *Aircraft model, performance, and initial state*: Trajectory prediction also depends on aircraft performance models and initial state assumptions. Models such as Base of Aircraft Data (BADA) provide representative aerodynamic and engine parameters, but cannot capture all aircraft-specific variability [29]. Initial state errors, particularly in aircraft mass, can propagate over the prediction horizon and affect climb and descent prediction accuracy [30, 31]. These effects are generally secondary to intent and atmospheric uncertainty in medium-term trajectory prediction, but they remain part of the overall prediction error [21, 31].

d) *Flight technical errors*: Imperfections in flight control systems such as the FMS and autopilot introduce flight technical errors. They are commonly represented as residual deviations around the nominal trajectory and are usually smaller than intent and atmospheric effects at the trajectory prediction level considered here [30, 31].

3) *Quantifying trajectory uncertainty*: Spatial trajectory prediction uncertainty can be represented as an ellipsoidal uncertainty region centred on the nominal trajectory. In a trajectory-aligned frame, the extent of this region in the along-track, cross-track, and vertical directions reflects prediction accuracy over the look-ahead horizon [32]. As illustrated in Figure 3, these regions typically grow with look-ahead time because prediction errors accumulate as the aircraft progresses along the trajectory.

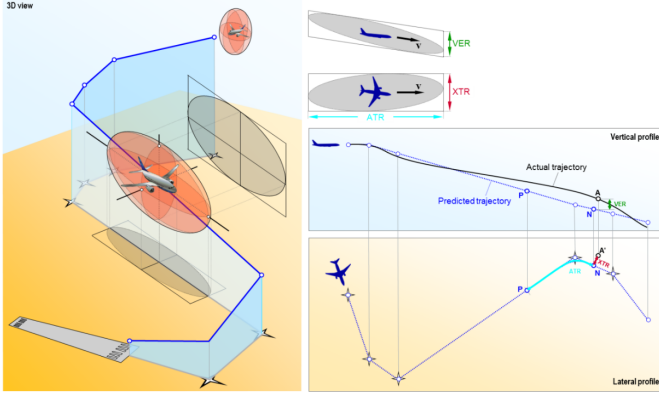


Figure 3. Spatial trajectory prediction uncertainty represented around a nominal trajectory [31].

This representation is useful for conflict management because it separates nominal encounter geometry from trajectory uncertainty. It also provides the basis for estimating separation infringement probability in probabilistic conflict detection.

D. Uncertainty and Conflict Management

Once trajectory uncertainty is represented around the nominal path, conflict management must decide over which time horizon this uncertainty should be evaluated. Short range detection concerns tactical alerts over seconds to minutes, while long range detection supports flow and traffic management. Between these levels, medium range detection typically spans approximately 8–20 minutes and supports strategic trajectory modification before immediate tactical intervention is required [33].

Within this medium-range horizon, nominal trajectory intersections alone are insufficient when prediction uncertainty differs between aircraft. Deterministic conflict detection evaluates separation along nominal trajectories and is computationally efficient [34]. However, it does not account for uncertainty growth around the predicted trajectory. Probabilistic methods instead estimate the likelihood of separation infringement by combining the nominal encounter geometry with trajectory prediction uncertainty [33, 35, 36]. The same uncertainty representation can also be retained during resolution, so that candidate manoeuvres are evaluated against both nominal separation and estimated separation infringement probability while limiting deviation from the planned trajectory [37, 38].

III. TRAJECTORY-BASED OPERATIONS SIMULATION MODEL

This section defines the simulation model used to evaluate how mixed datalink capability affects trajectory management in simulated Amsterdam ACC. Subsection III-A first introduces the framework and its CD&R cycle. The remaining subsections define equipage-dependent prediction uncertainty, prediction rebuild logic, probabilistic conflict detection, conflict resolution, and arrival time monitoring.

A. Simulation Framework Overview

A simulation-based TBO model is implemented in the BlueSky ATM simulator developed by Hoekstra et al. [39]. The model covers Amsterdam ACC between FL110 and FL260. The flown trajectory represents aircraft truth, while the active 4D reference trajectory represents the ground system prediction used for CD&R and arrival time monitoring.

The framework uses two setup steps. First, the Monte Carlo initialisation assigns the traffic sample, equipage class, arrival intent, and wind inputs for one run. Each run is one execution of a traffic sample within the larger Monte Carlo batch. For each arrival, sampled intent consists of the fixed descent angle γ and target descent speed V_{CAS} . A forecast and realised wind field pair is also selected from the available wind data.

Second, the initial active reference trajectory is generated from the forecast wind field, predictor available intent, and aircraft route capability. Route capability distinguishes route-constrained ATN B1 aircraft, which follow available Standard Instrument Departures (SIDs) and Standard Arrival Routes (STARs) through the ACC, from FANS 1/A and ATS B2 aircraft. For these higher capability classes, lower prediction uncertainty and higher trajectory update capability enable shorter flexible routes outside the published SID and STAR structure. The assumptions are summarised in Table II.

Table II
FUNCTIONAL EQUIPAGE ASSUMPTIONS FOR PREDICTOR ACCESS, HIDDEN INTENT, AND TRAJECTORY UPDATE CAPABILITY.

Equipage class	Predictor access	Hidden intent	Route and update capability
ATN B1	Filed route and current state	γ, V_{CAS}	Existing LVNL route points
FANS 1/A	γ and derived ToD via IPI	V_{CAS}	Flexible route updates
ATS B2	γ, V_{CAS} , and derived ToD via EPP	–	Flexible route updates

Together, the Monte Carlo initialisation and initial prediction setup define the upper part of the framework shown in Figure 4. In this setup, the realised wind field and sampled intent feed BlueSky execution, while the forecast wind field and predictor available intent feed the ground-based prediction. The sampled execution intent is therefore not necessarily equal to the intent used in the predicted trajectory.

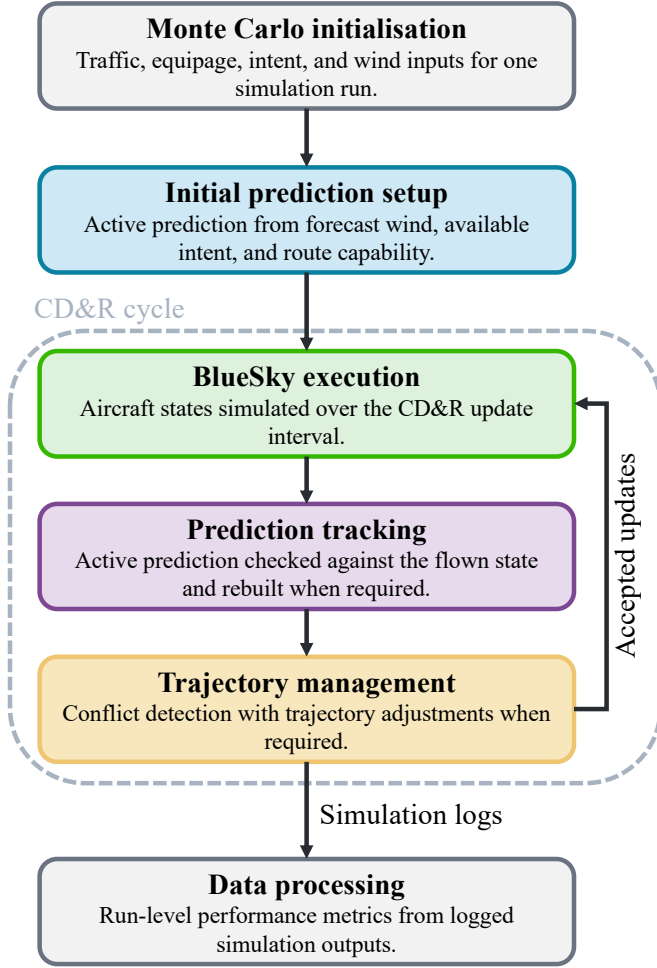


Figure 4. Schematic overview of the TBO simulation framework.

The resulting inputs are then used in the repeated CD&R cycle shown in the lower part of Figure 4. BlueSky execution provides the flown aircraft states under sampled intent and realised wind conditions. Prediction tracking compares these states with the active reference trajectories and rebuilds a prediction when the deviation exceeds the prescribed thresholds. Trajectory management uses the active reference trajectories and their associated uncertainty representation to detect conflicts. If a threshold-exceeding conflict is identified, the resolution module evaluates candidate trajectory updates, and accepted updates replace the relevant active reference trajectories for later cycles.

Arrival time monitoring is included as a secondary trajectory management objective for inbound aircraft. When no conflict is present, or when multiple conflict-free resolution candidates are available, speed adjustments may be used to reduce deviations from the assigned Expected Approach Time (EAT). Data processing converts the logged simulation outputs into run-level performance metrics. The following subsections describe the model components in sequence: equipment-dependent prediction uncertainty in Subsection III-B, prediction tracking logic in Subsection III-C, conflict detection in Subsection III-D, trajectory resolution in Subsection III-E, and arrival time monitoring in Subsection III-E3.

B. Equipment-Dependent Prediction Uncertainty

Equipment class affects prediction uncertainty through the intent information available to the predictor. Each predicted trajectory is assigned time-dependent along-track, cross-track, and vertical dispersion in the trajectory-aligned frame, denoted by a , c , and v respectively. For the along-track and vertical components, the total variance is decomposed into intent and execution uncertainty, as shown in Equations (1) and (2):

$$\sigma_a^2(t) = \sigma_{a,intent}^2(t) + \sigma_{a,exec}^2(t) \quad (1)$$

$$\sigma_v^2(t) = \sigma_{v,intent}^2(t) + \sigma_{v,exec}^2(t). \quad (2)$$

Intent uncertainty represents sampled arrival intent that is not available to the ground-based predictor. Execution uncertainty represents the remaining prediction uncertainty after the available intent information has been applied, primarily due to mismatch between the forecast and actual wind field. Intent uncertainty therefore depends on hidden trajectory information, whereas execution uncertainty remains even after the available intent has been incorporated. The variance terms in Equations (1) and (2), together with the cross-track component below, form the diagonal covariance terms used by the conflict detection model.

Cross-track intent uncertainty is not modelled, because the lateral route used by the predictor is assumed to be known after the route representation has been selected. The remaining cross-track uncertainty represents bounded lateral path-keeping error during execution, under the assumption that the FMS keeps the aircraft within a lateral tracking margin. This bound is represented by $\bar{\sigma}_c$ in Equation (3) [33]:

$$\sigma_c^2(t) = \sigma_{c,exec}^2(t) = \min \{r_c^2 s^2(t), \bar{\sigma}_c^2\} \quad (3)$$

The remaining uncertainty representation is defined in two parts. Subsection III-B1 specifies how unavailable arrival intent introduces vertical and along-track variance through the fixed FPA descent angle and target descent speed. Subsection III-B2 then defines the remaining execution uncertainty around the predicted trajectory after the predictor has incorporated the intent available under the assigned equipment class.

1) *Arrival intent uncertainty*: The arrival intent model uses two sampled parameters: the fixed FPA descent angle γ and the target descent CAS V_{CAS} . These sampled values define the execution intent followed by the aircraft in the simulation. Equipment does not affect the generation of this execution intent, but determines whether the sampled intent is available to the ground-based trajectory predictor.

As indicated by the hidden intent entries in Table II, only sampled parameters unavailable to the predictor contribute to intent uncertainty. If a sampled parameter is available, it is used directly in the predicted trajectory. If it is unavailable, the predictor uses the corresponding nominal value, and the difference between the nominal and sampled trajectories contributes to the intent variance. The ToD is not sampled independently, but is derived from the descent angle, cruise altitude, and Initial Approach Fix (IAF) altitude constraint.

This sampled intent is common to all equipment classes, only predictor access to that intent differs. For ATN B1, both vertical

and along-track arrival intent variance are active. For FANS 1/A, only along-track intent variance is active. For ATS B2, no arrival intent variance is added. If a speed instruction is issued during the simulation, the instructed target descent CAS is treated as known to the predictor from that point onward.

The normally distributed intent variables γ and V_{CAS} are evaluated at deterministic intent values indexed by q , with values γ_q or $V_{\text{CAS},q}$ and weights w_q . These values and weights are obtained using nine-point Gauss–Hermite quadrature. The nominal values are denoted by γ_{nom} and $V_{\text{CAS,nom}}$. The resulting intent value trajectories differ through the aircraft-specific route, altitude profile, and wind profile.

a) Vertical intent uncertainty: Vertical intent uncertainty follows from uncertainty in the fixed descent angle γ . For the same cruise altitude and IAF constraint, a shallower descent angle increases the required descent distance and moves the derived ToD upstream, while a steeper descent angle shortens the descent distance and moves the derived ToD downstream. The geometric effect of this sampled descent angle is shown in Figure 5. The nominal trajectory is therefore used as the centre of the vertical intent distribution, and the sampled descent angles define a family of possible vertical profiles around this nominal profile.

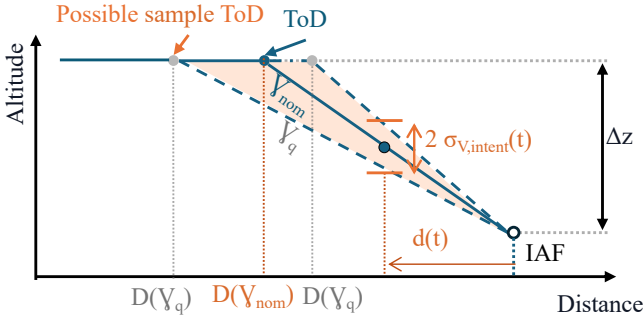


Figure 5. Vertical uncertainty representation for fixed FPA descent, where uncertainty in the selected descent angle changes the derived ToD and the resulting altitude profile.

The descent angle distribution is based on the fixed FPA descent trials of Itoh et al. [16], which evaluated operational descent angles over a similar range, approximately 2.0° – 3.5° . The nominal value and standard deviation are adjusted to define a central normal distribution, with $\gamma_{\text{nom}} \pm 3\sigma_\gamma$ covering the main part of this tested range:

$$\gamma \sim \mathcal{N}(\gamma_{\text{nom}}, \sigma_\gamma^2), \quad \gamma_{\text{nom}} = 2.6 [^\circ], \quad \sigma_\gamma = 0.2 [^\circ]. \quad (4)$$

For each intent value γ_q , the descent distance $D(\gamma_q)$ from the derived ToD to the IAF is computed as

$$D(\gamma_q) = \frac{z_{\text{cruise}} - z_{\text{IAF}}}{\tan(\gamma_q)}. \quad (5)$$

This distance defines the vertical position profile $z_q(t)$ associated with intent value q along the planned route. The corresponding nominal vertical position profile is denoted by $z_{\text{nom}}(t)$. The vertical intent variance is computed as the weighted squared deviation between the intent value vertical position profiles and the nominal profile. The vertical variance is

therefore computed from the spread of possible altitude profiles around the nominal predictor profile.

$$\sigma_{v,\text{intent}}^2(t) \approx \sum_q w_q [z_q(t) - z_{\text{nom}}(t)]^2. \quad (6)$$

b) Along-track intent uncertainty: The same principle is applied to target descent speed, but its effect appears mainly as along-track timing uncertainty rather than vertical profile uncertainty. Along-track intent uncertainty is induced by uncertainty in the target descent CAS, which shifts the Mach/CAS crossover altitude and changes the ground speed profile. The constant Mach segment is short relative to the subsequent constant CAS segment and may be absent for low target CAS values. Therefore the Mach number is not sampled separately and kept fixed at $M_{\text{des}} = 0.78$ to maintain a consistent speed schedule. The model therefore attributes arrival speed intent uncertainty to the target descent CAS, which is the main driver of along-track timing variation in the evaluated profiles.

The nominal target descent CAS is selected as the midpoint of the considered operational range, 230–310 kt, and is consistent with the average speed control values around 265–280 kt evaluated in the fixed FPA descent trials of Itoh et al. [16]. The standard deviation is adjusted such that $V_{\text{CAS,nom}} \pm 3\sigma_{V_{\text{CAS}}}$ approximately spans this range. The target CAS distribution is defined as

$$V_{\text{CAS}} \sim \mathcal{N}(V_{\text{CAS,nom}}, \sigma_{V_{\text{CAS}}}^2), \quad (7)$$

$$V_{\text{CAS,nom}} = 270 [\text{kt}], \quad \sigma_{V_{\text{CAS}}} = 13.3 [\text{kt}].$$

For each intent value $V_{\text{CAS},q}$, the Mach/CAS crossover altitude $h_{x,q}$ is recomputed from the selected CAS and fixed descent Mach number M_{des} [15]. The along-track position corresponding to each intent value is then obtained from the ground speed profile:

$$s_q(t) = \int_{t_0}^t V_{\text{GS}}(\tau; V_{\text{CAS},q}, h_{x,q}, V_{w,\parallel,q}) d\tau. \quad (8)$$

Here, $h_{x,q}$ is the crossover altitude associated with intent value q , and $V_{w,\parallel,q}$ is the along route wind component. The ground speed V_{GS} is therefore a function of the CAS-based TAS schedule and the wind component along the route. The along-track intent variance is computed from the weighted squared difference between each intent value trajectory and the nominal trajectory $s_{\text{nom}}(t)$:

$$\sigma_{a,\text{intent}}^2(t) \approx \sum_q w_q [s_q(t) - s_{\text{nom}}(t)]^2. \quad (9)$$

The resulting vertical and along-track intent variances, $\sigma_{v,\text{intent}}^2(t)$ and $\sigma_{a,\text{intent}}^2(t)$, are dispersion measures around the predicted trajectory. This representation introduces two approximations. First, descent speed uncertainty is represented by a marginal along-track variance, although the transformation from CAS to ground speed is not strictly Gaussian. Second, descent angle uncertainty is represented by a marginal vertical variance, although the altitude distribution around the ToD is truncated by the cruise altitude before descent initiation. This may overstate upward dispersion near the ToD. In the selected scenarios, this effect is expected to be limited for most arrivals

because the nominal ToD generally lies above the controlled airspace.

2) *Wind-driven execution uncertainty*: Execution uncertainty represents the additional prediction dispersion attributed to atmospheric conditions after the predictor has incorporated the intent information available for the aircraft equipage class. In this model, only wind-driven dispersion is represented, through mismatch between the forecast and realised wind fields. For arrivals, the implementation follows the fixed FPA uncertainty model of Blom [26]. For departures, the along-track component follows the trajectory prediction error analysis of Mondoloni et al. [27].

Along-track execution uncertainty is represented by an equivalent ground speed error. The parameter $r_{a,exec}$ is therefore a standard deviation growth rate with units of velocity. Since the corresponding position error accumulates linearly in elapsed prediction time, the along-track variance grows quadratically:

$$\sigma_{a,exec}^2(t) = r_{a,exec}^2 t^2. \quad (10)$$

The value of $r_{a,exec}$ depends on flight phase. For arrivals, separate values are used for cruise and fixed FPA descent [26]. For departures, a constant ground speed bias is used from Mondoloni et al. [27].

Vertical execution uncertainty is accumulated only during active arrival descent, where wind-driven dispersion is represented as a direct vertical variance growth term. In contrast to the along-track formulation, $r_{v,exec}$ is a variance growth rate with units of squared distance per unit time, so the variance grows linearly with elapsed time in active descent:

$$\sigma_{v,exec}^2(t) = r_{v,exec} t_{des}. \quad (11)$$

In Equation (11), t_{des} is the elapsed time in active descent. No separate vertical execution uncertainty term is added for departures, since the wind-driven departure uncertainty is represented through along-track timing dispersion. Wind mismatch may place a departing aircraft earlier or later along the climb profile, but the corresponding altitude difference is coupled to the along-track error rather than treated as an independent vertical uncertainty source. Because the conflict detection model uses a diagonal covariance approximation, this coupled contribution is not retained as a separate vertical covariance term.

The execution uncertainty parameters used in Equations (3), (10) and (11) are summarised in Table III [26, 27].

Table III
EXECUTION UNCERTAINTY PARAMETERS USED IN THE VARIANCE MODEL. THE CROSS-TRACK PARAMETERS APPLY TO ALL FLIGHT PHASES.

Applicability	$r_{a,exec}$ [m/s]	$r_{v,exec}$ [m ² /s]	r_c [-]	$\bar{\sigma}_c$ [NM]
Departure	5.144	0.00	—	—
Arrival cruise	1.374	0.00	—	—
Arrival fixed FPA descent	0.358	1.49	—	—
All phases	—	—	1/57	0.5

C. Prediction Tracking and Rebuild Logic

The uncertainty model defines the dispersion around the active prediction, while the rebuild logic determines when the centre of that prediction is reset to the current aircraft state. At

each update cycle, the realised aircraft position is compared with the time-coincident point on the active predicted trajectory in the trajectory-aligned frame, as explained in Subsection II-C1. The predicted trajectory is rebuilt when the deviation exceeds one of the prescribed along-track, cross-track, or vertical thresholds. The threshold values will be defined in Subsection IV-C.

When a rebuild is triggered, the predicted trajectory is regenerated from the current aircraft state using the predictor access rules defined in Table II. The current state is treated as the new prediction anchor, so trajectory error accumulation is re-initialised from the rebuild time. Subsequent intent and execution uncertainty are propagated along the rebuilt predicted trajectory, which is then used in later CD&R cycles.

D. Conflict Detection Method

The conflict detection method estimates the probability that two predicted aircraft trajectories infringe the prescribed protection zone. It combines the nominal encounter geometry with the time-dependent uncertainty components defined in Subsection III-B. Conceptually, the method converts the two aircraft prediction uncertainties into a relative position uncertainty and then estimates the probability that this relative position enters the cylindrical protection zone during the look-ahead window. The method follows the analytical framework of Paielli et al. [35] and the three-dimensional extension by Li et al. [36]. The concept is illustrated in Figure 6.

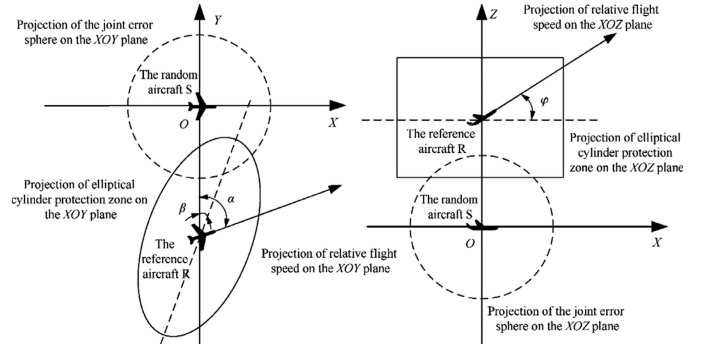


Figure 6. Schematic illustration of the conflict detection concept between aircraft R and S under trajectory prediction uncertainty [36].

The uncertainty components from Subsection III-B are applied around each aircraft's predicted trajectory. For aircraft i , the local prediction error in the trajectory-aligned frame Θ_1 is modelled as

$$\tilde{q}_{\Theta_1}^i(t) \sim \mathcal{N}(\mathbf{0}, S_{\Theta_1}^i(t)). \quad (12)$$

The zero-mean assumption means that the predicted trajectory is used as the centre of the uncertainty distribution after the predictor access rules in Table II have been applied. The local covariance matrix is defined by the along-track, cross-track, and vertical variance components:

$$S_{\Theta_1}^i(t) = \begin{bmatrix} \sigma_{a,i}^2(t) & 0 & 0 \\ 0 & \sigma_{c,i}^2(t) & 0 \\ 0 & 0 & \sigma_{v,i}^2(t) \end{bmatrix}. \quad (13)$$

The covariance matrix is kept diagonal to retain an analytically tractable conflict probability calculation. This is an approximation for fixed FPA arrivals, because hidden descent angle and

target descent speed can induce coupled along-track and vertical prediction errors. Their effects are included in the marginal variance terms, but the corresponding cross-covariance terms are not retained in Equation (13).

The next step is to combine the two aircraft uncertainties into a single relative position distribution. For pairwise conflict detection, the aircraft positions are first expressed in a common ground-fixed reference frame. The nominal relative position between aircraft S and reference aircraft R is defined in Equation (14):

$$\Delta \mathbf{p}_g(t) = \mathbf{p}_g^S(t) - \mathbf{p}_g^R(t). \quad (14)$$

Since both aircraft positions are modelled as Gaussian random variables, the relative position is also Gaussian:

$$\Delta \mathbf{p}_g(t) \sim \mathcal{N}(\boldsymbol{\mu}(t), \mathbf{Q}(t)), \quad (15)$$

where $\boldsymbol{\mu}(t)$ is the nominal relative position. Assuming statistically independent prediction errors between aircraft, the relative covariance matrix is obtained from Equation (16):

$$\mathbf{Q}(t) = \mathbf{S}_g^S(t) + \mathbf{S}_g^R(t). \quad (16)$$

The instantaneous conflict probability is the probability mass of the relative position distribution inside the protection zone volume V_{PZ} :

$$P_C(t) = \iiint_{V_{PZ}} p(x, y, z) dx dy dz, \quad (17)$$

where $p(x, y, z)$ is the probability density function of Equation (15). A conflict is detected when the maximum probability over the look-ahead horizon exceeds the prescribed threshold:

$$\max_{t \in [T_{\min}, T_{\max}]} P_C(t) > P_{C, \text{thr}}. \quad (18)$$

Here, $T_{\min}$ and $T_{\max}$ define the conflict detection look-ahead window, and $P_{C, \text{thr}}$ is the conflict probability threshold. This threshold is treated as a tunable model parameter because it controls the strictness of the CD&R logic: lower values lead to earlier and more frequent interventions, whereas higher values restrict interventions to encounters with larger estimated conflict probability. Its selected value is determined through the threshold sensitivity analysis in Section V.

Direct analytical evaluation of Equation (17) is intractable because the Gaussian density is integrated over a cylindrical protection zone. The approximation proposed by Li et al. [36] is therefore used. The relative covariance matrix is factorised using the Cholesky decomposition in Equation (19):

$$\mathbf{Q}(t) = \mathbf{L}(t)\mathbf{L}^T(t). \quad (19)$$

A whitening transformation maps the relative position uncertainty to a standard normal distribution. Under this transformation, the cylindrical protection zone becomes an elliptical cylinder. A horizontal rotation aligns the principal axes of the ellipse with the coordinate axes, after which the elliptical cylinder is over-approximated by an axis-aligned rectangular box.

In the transformed coordinate system, the conflict probability is approximated by the product of three one-dimensional normal probability integrals:

$$P_C(t) \approx \int_{-\Delta x - x_{\max}}^{-\Delta x + x_{\max}} \int_{-\Delta y - y_{\max}}^{-\Delta y + y_{\max}} \int_{-\Delta z - h'/2}^{-\Delta z + h'/2} \phi(x) \phi(y) \phi(z) dz dy dx. \quad (20)$$

where $\phi(\cdot)$ denotes the standard normal probability density function. The terms Δx , Δy , and Δz are the components of the transformed nominal relative position after whitening and horizontal axis alignment. The parameters $x_{\max}$ and $y_{\max}$ are the half-widths of the rectangular overbound of the transformed horizontal protection zone, and h' is the transformed vertical extent of the protection zone. The rectangular approximation geometrically over bounds the transformed protection zone and is therefore conservative with respect to the rectangular overbound of the transformed protection zone probability. This approximation gives a tractable, conservative estimate of the probability that the uncertain relative position lies inside the protection zone.

E. Conflict Resolution Logic

When the maximum conflict probability over the look-ahead horizon exceeds the threshold in Equation (18), the resolution module modifies one or more active reference trajectories. Only conflicts whose relevant risk interval lies within the Amsterdam ACC control volume, FL110–FL260, are considered. Candidate resolutions are generated from the current time-coincident point on the active reference trajectory and replace only the future trajectory segment. Accepted candidates become the new active reference trajectory for subsequent detection and resolution cycles. The resolution module therefore acts only after detection has identified a threshold-exceeding conflict within the modelled control volume.

Candidate manoeuvres are evaluated with the probabilistic conflict detection method defined in Subsection III-D. This follows the general CD&R principle that separation is restored by modifying aircraft trajectories while limiting deviation from the intended path [33, 34], and is consistent with probabilistic CD&R formulations in which candidate manoeuvres are screened under trajectory uncertainty [37, 38]. The primary objective is removal of threshold-exceeding conflicts. Among feasible candidates, the model prefers the smallest deviation from the active route and arrival time.

1) *Resolution strategies:* Candidate strategies are evaluated in a fixed preference order: speed first, then level-off, and finally lateral resolution. Speed control is treated as the least intrusive option, because it preserves both the lateral route and the prescribed vertical geometry. Level-off manoeuvres are considered next because they modify the vertical profile but leave the lateral route unchanged. Lateral manoeuvres are used last because they alter the route geometry and increase flown distance. Level-off and lateral candidates may be combined with speed control to improve separation or arrival time adherence, consistent with the trajectory management logic applied by Ottenhoff [19].

In the speed mode, the planned speed schedule is replaced by a speed candidate selected from the set later defined in Subsection IV-C. For fixed FPA arrivals, this candidate is a target descent CAS. If the aircraft is still above the relevant Mach/CAS crossover altitude, the speed change is introduced from the new crossover point. Otherwise, the aircraft accelerates or decelerates from its current position. This changes trajectory timing and the resulting ROCD, but not the lateral route or prescribed vertical path. Because the crossover point may lie above the modelled Amsterdam ACC control volume, the model assumes that such arrival speed instructions can be coordinated with neighbouring Air Navigation Service Providers (ANSPs).

In the level-off mode, an altitude hold is inserted into the vertical profile as a strategic trajectory update. The level-off must be feasible within FL110–FL260 and must preserve downstream altitude constraints, including the IAF constraint for arrivals. This mode is only modelled for FANS 1/A and ATS B2 aircraft, because the model assumes that the altitude hold and its transition points can be communicated through FMS-integrated digital trajectory updates.

In the lateral mode, the horizontal route is modified using a two leg resolution concept, as illustrated in Figure 7. This provides a compact parameterisation in which the aircraft leaves the active trajectory, passes through an intermediate resolution point, and subsequently rejoins the planned route or proceeds towards the relevant merge point [19, 34]. Candidate manoeuvres are generated through a grid search from the current aircraft position, or from the first position inside the control bounds, towards the relevant endpoint.

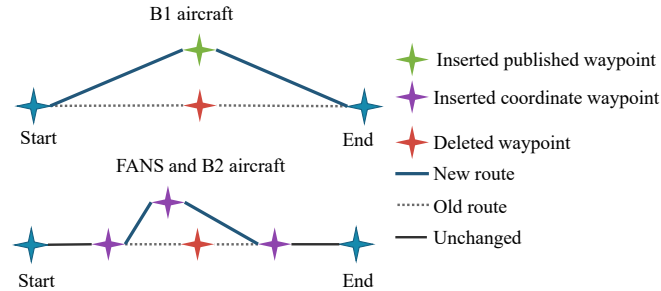


Figure 7. Two-leg lateral resolution strategy for ATN B1 and FANS/ATS B2 aircraft. ATN B1 uses published route waypoints, while FANS 1/A and ATS B2 may use exact leave, intermediate, and merge coordinates.

The feasible lateral candidates depend on whether the aircraft can receive arbitrary trajectory points or only waypoint-constrained instructions. The equipage-dependent route capability defined in Subsection III-A determines the lateral candidate set. For ATN B1 aircraft, the search is restricted to published route waypoints. This reflects the limited ability to communicate arbitrary trajectory modifications to aircraft without FMS integrated trajectory clearance capability. For FANS 1/A and ATS B2 aircraft, the leave point, intermediate resolution point, and merge point are instead selected from an exact coordinate grid. This allows the lateral resolution to be constructed independently of the existing route structure, consistent with the CPDLC-enabled digital trajectory update capability assumed for these equipage classes.

2) *Multi-aircraft conflicts*: Because simultaneous multi-aircraft optimisation is outside the scope of this model, connected conflicts are resolved sequentially as a heuristic. Connected conflicts that share one or more aircraft are treated as a conflict cluster. The cluster is resolved sequentially, starting with the pair that has the highest peak conflict probability. Candidate manoeuvres are generated for that pair, then checked against the remaining aircraft in the cluster and against newly introduced conflicts within the look-ahead horizon.

A candidate is feasible if it removes the triggering threshold exceedance, does not introduce a new threshold exceedance, and satisfies the constraints of the selected manoeuvre type. If multiple feasible candidates remain, selection follows the objective hierarchy of the resolution module: conflict removal first, then minimum trajectory deviation and improved EAT adherence where applicable. If no feasible candidate removes the triggering exceedance, the best residual candidate is accepted if it reduces the peak conflict probability without introducing a new threshold exceedance. This fallback preserves the sequential resolution logic while avoiding rejection of partial improvements. This sequential treatment is an order-dependent heuristic approximation of multi-aircraft CD&R [37, 38].

3) *Arrival Time Monitoring*: Arrival time monitoring is included to check whether conflict resolution and speed corrections preserve the assigned EAT at the IAF. The model therefore monitors whether arriving aircraft remain within the assigned EAT tolerance, so that trajectory management does not unnecessarily disrupt the planned arrival sequence.

When no conflict is present, the model evaluates the same descent speed candidates used for conflict resolution and accepts a speed adjustment only if it reduces the predicted EAT deviation without introducing a threshold-exceeding conflict. During conflict resolution, separation remains the primary objective, but among conflict-free candidates the model gives preference to solutions that also preserve the assigned EAT. The corresponding tolerance and evaluation metric are defined in Subsection IV-D.

IV. METHODOLOGY

This section defines the experimental setup used to evaluate the TBO simulation model from Section III. It describes the experimental design, traffic scenarios, equipage compositions, Monte Carlo sampling, controlled parameters, performance metrics, hypotheses, and assumptions.

A. Experimental Design

The experiment varies two independent variables: traffic load and functional equipage composition. Three traffic load scenarios and three equipage compositions are evaluated, resulting in nine experimental conditions. Each condition is simulated using 300 Monte Carlo replications. The replication count is justified by the convergence check later described in Subsection IV-B.

For each traffic load scenario, the nominal traffic sample is fixed. For each equipage composition, the class fractions are fixed. A common set of Monte Carlo seeds is used across the three equipage compositions within each traffic load scenario, such that equipage effects can be compared under equivalent sampled realisations.

1) *Traffic load scenarios*: The selected traffic samples represent light, moderate, and dense morning traffic in Amsterdam ACC sectors 1 and 2, which are shown in Figure 8. The sector geometry is constrained by restricted airspace within the Dutch FIR that is not available to Amsterdam ACC. These unavailable regions influence the available route structure and can concentrate traffic near the evaluated domain boundaries. All scenarios are derived from real traffic samples from the morning arrival period between 06:30 and 08:30 local time and contain both inbound and outbound traffic. Arrival aircraft are initialised 20 minutes before their observed ToD. Outbound aircraft are initialised at take-off time and retained until 20 minutes after their observed Top of Climb (ToC).

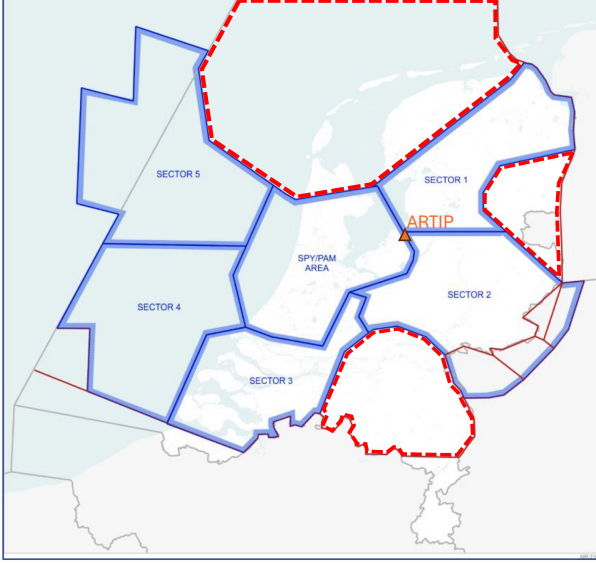


Figure 8. Amsterdam ACC sectors, with sectors 1 and 2 in the east and the used IAF, ARTIP. Restricted airspace unavailable to Amsterdam ACC is shown by dashed red boundaries, adapted from Luchtverkeersleiding Nederland [40].

The nominal trajectory samples are preprocessed before the final traffic load characteristics are extracted. This removes infeasibilities outside the modelled ACC control volume that would otherwise enter the evaluation, such as conflicts initiated above or below FL110–FL260. Since the CD&R model neither resolves conflicts outside this volume nor includes cruise speed control, these infeasibilities are handled through limited shifts in aircraft creation times. The resulting traffic load characteristics are reported in Table IV, where the arrival-count percentile indicates each sample’s position within the distribution of valid candidate windows.

Table IV
PREPROCESSED TRAFFIC LOAD SCENARIO CHARACTERISTICS FOR THE SELECTED
06:30–08:30 LOCAL TIME WINDOW WITHIN SECTORS 1 AND 2.

	Light	Moderate	Dense
Number of arrivals [-]	39	47	55
Arrival count percentile [%]	12.3	42.4	96.2
Number of departures [-]	11	34	34
Peak simultaneous aircraft within ACC [-]	8	12	15

The same shifts are used where necessary to keep the assigned EATs reachable within ± 120 s for all equipage types under the

simplified arrival model. The assigned EATs are otherwise preserved to retain the observed arrival pressure and traffic demand, while preventing boundary-crossing conflicts from dominating the evaluation.

2) *Equipage compositions*: The second independent variable is the functional equipage composition. Each composition is defined by $(p_{B1}, p_{FANS}, p_{B2})$, where the fractions sum to unity. The compositions are informed by reported and projected air-ground datalink equipage levels in Schiphol arrival traffic from Subsection II-A. They represent functional capability available to the model, rather than a direct reproduction of formal aircraft equipage. The functional interpretation of each class follows Subsection II-A and Table II. Although aircraft may be dual equipped in practice, each simulated aircraft is assigned a single functional equipage class.

Table V
FUNCTIONAL EQUIPAGE COMPOSITIONS EVALUATED IN THE EXPERIMENTAL SETUP.

	Baseline capability	Medium capability	High capability
p_{B1} [%]	45	25	10
p_{FANS} [%]	50	45	30
p_{B2} [%]	5	30	60

B. Monte Carlo Sampling

Three quantities are sampled in each Monte Carlo run. First, wind field mismatch is represented by sampling one of 178 valid Royal Netherlands Meteorological Institute (KNMI) forecast–analysis pairs from 18 days across March, August, and December 2025, and January, February, March, and April 2026. The trajectory predictor uses the 4 h ahead forecast, while BlueSky uses the corresponding actual 0 h wind conditions. Second, aircraft equipage is sampled independently according to the composition of the experimental condition. Third, arrival intent is sampled for all inbound aircraft using the fixed FPA descent angle and target descent CAS defined in Subsection III-B.

Monte Carlo convergence is assessed from the cumulative development of the primary performance metrics over the replications. The accepted-adjustment, track-distance, work, and EAT error metrics stabilise before the final replication count. For metrics with a non-zero median, the 95% confidence interval half-width remains within 5% of the corresponding median. Residual Loss of Separation (LoS) is evaluated separately because its sparse occurrence makes this criterion unsuitable. Instead, convergence is checked from the stabilisation of the mean residual count and the paired seed-wise comparison.

C. Controlled Variables

Table VI lists the main controlled parameters. Aircraft types are fixed within each traffic scenario and are sampled independently of equipage class. This isolates functional equipage effects from aircraft performance effects.

D. Dependent Variables and Statistical Analysis

The dependent variables are grouped into safety, intervention demand, and operational efficiency. Safety is evaluated using residual LoS events, counted when the relative position of one

Table VI
CONTROLLED PARAMETERS USED ACROSS ALL EXPERIMENTAL CONDITIONS.

Parameter	Value
Modelled airspace	Amsterdam ACC sectors 1 and 2
Simulation vertical domain	FL110–FL260
CD&R cycle interval	30 [s]
CD&R look-ahead window	8–20 [min]
Conflict probability threshold	10 [%]
Protection zone horizontal radius	5 [NM]
Protection zone vertical half-height	1000 [ft]
Rebuild thresholds	0.25 [NM] along-track, 0.5 [NM] cross-track, 250 [ft] vertical
EAT tolerance	120 [s]
Speed candidate set	230–310 [kt] in 5 [kt] steps
Aircraft performance model	BADA 3.14
Arrival boundary condition	FL100 at the IAF with EAT

aircraft enters the cylindrical protection zone of another aircraft, using the dimensions in Table VI. Events that originate outside the modelled FL110–FL260 control volume and continue into the evaluation domain are excluded from the residual LoS metric and reported separately, because the CD&R model does not resolve conflicts outside the control volume. Repeated LoS events for the same aircraft pair are counted only when at least one minimum look-ahead horizon, 8 min, has elapsed since the previous episode.

Intervention demand is evaluated using the number of accepted trajectory adjustments, both in aggregate and by manoeuvre type. Operational efficiency is evaluated using total flown track distance and cumulative thrust-distance work per aircraft above FL110. This evaluation domain is broader than the FL110–FL260 conflict resolution domain, because upstream trajectory changes can still affect the aircraft state, path length, or residence time above FL110. Arrival time adherence is evaluated as a secondary operational check of whether equipage-dependent trajectory updates affect the assigned EAT.

The work metric is based on BlueSky’s accumulated work calculation and is used only as a relative indicator between experimental conditions, not as exact fuel burn or an absolute energy efficiency metric. For each aircraft, the accumulated work above FL110 is computed as

$$W_i = \int_{t_{i,110}^{\text{in}}}^{t_{i,110}^{\text{out}}} T_i(t) \sqrt{V_{\text{GS},i}^2(t) + \dot{h}_i^2(t)} dt, \quad (21)$$

where $t_{i,110}^{\text{in}}$ and $t_{i,110}^{\text{out}}$ denote the times at which aircraft i enters and leaves the efficiency evaluation domain above FL110, $T_i(t)$ is the modelled thrust, $V_{\text{GS},i}(t)$ is ground speed, and $\dot{h}_i(t)$ is vertical speed. The scenario-level metric is the mean work per aircraft:

$$\bar{J}_W = \frac{1}{N_{110}} \sum_{i \in \mathcal{A}_{110}} W_i, \quad (22)$$

where $\mathcal{A}_{110}$ is the set of aircraft included in the efficiency evaluation above FL110 and N_{110} is the number of aircraft in this set. Work accumulated below FL110 is excluded.

Results are reported separately for each traffic load scenario and equipage composition. Because common Monte Carlo seeds are used across equipage compositions within each traffic load

scenario, equipage effects are evaluated through paired seed-wise comparisons. Page’s test, an ordered extension of the Friedman test, is used to statistically test whether accepted trajectory adjustments, flown track distance, and modelled work decrease monotonically with increasing functional capability [41].

E. Hypotheses

The hypotheses are formulated around the expected effect of increasing ADS-C intent availability and FMS-integrated CPDLC trajectory update capability. It is hypothesised that increasing ADS-C intent availability and FMS-integrated CPDLC trajectory update capability will:

- H1: reduce intervention demand, measured by accepted trajectory adjustments.*
- H2: decrease residual separation risk, measured by residual LoS events.*
- H3: improve operational efficiency above FL110, measured by total flown track distance and mean modelled thrust-distance work per aircraft.*

F. Assumptions

The experimental setup is based on the following modelling assumptions, which define the scope of the analysis:

- 1) Trajectory prediction errors are represented by the Gaussian, mutually uncorrelated along-track, cross-track, and vertical components.
- 2) The CD&R process is centralised and has instantaneous access to aircraft states and to the intent information available for each equipage class.
- 3) Aircraft are represented as point masses with fixed cylindrical protection zones.
- 4) ADS-C and CPDLC information is assumed to be available without message loss, latency, or communication failure.
- 5) All aircraft operate under nominal conditions, without weather avoidance, emergency procedures, or non-standard controller interventions.
- 6) Arrival trajectories are represented by the fixed FPA model with aircraft delivered to the IAF at FL100 and assigned an EAT.
- 7) Equipage class is sampled independently of aircraft type.
- 8) Cruise Mach and descent Mach are known and fixed.

V. RESULTS

This section presents the results. It first evaluates the uncertainty behaviour and conflict probability threshold used in the CD&R model. The remaining results compare the nine traffic-density and equipage-composition conditions for conflict management, operational efficiency, and EAT adherence.

A. Uncertainty Model Behaviour

Before the main scenario results, the uncertainty behaviour is assessed to verify that the model produces reasonable magnitudes and trends. The implemented parameterisation is evaluated for the vertical and along-track components using a common nominal descent under the three equipage configurations. Figure 9 shows the vertical uncertainty around the reference descent.

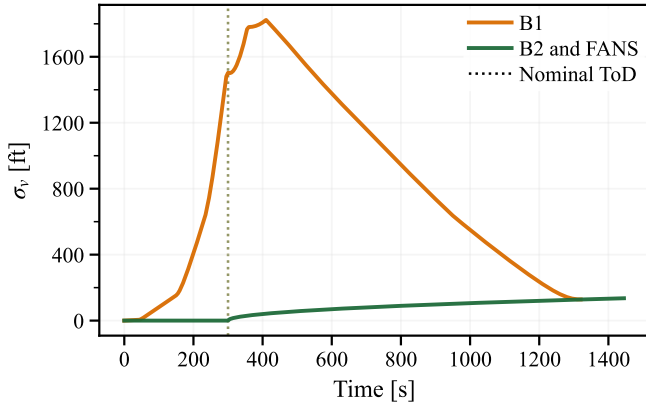


Figure 9. One standard deviation vertical uncertainty for the reference descent from FL380 to FL110.

Uncertainty increases before the nominal ToD, because shallower sampled descent angles can initiate descent earlier than the nominal profile. After all sampled profiles have reached their derived ToDs, the vertical uncertainty decreases towards the altitude-constrained IAF, where the descent angle intent spread vanishes and only the execution uncertainty remains.

Figure 10 shows the along-track uncertainty for the same nominal descent. Before the nominal ToD, the equipage configurations follow the same along-track execution uncertainty. After the nominal ToD, the uncertainty increases strongly for B1 and FANS because the target descent CAS is unknown. For B2, this intent component is available, so the remaining change in uncertainty is mainly driven by the different execution uncertainty growth rates in cruise and descent.

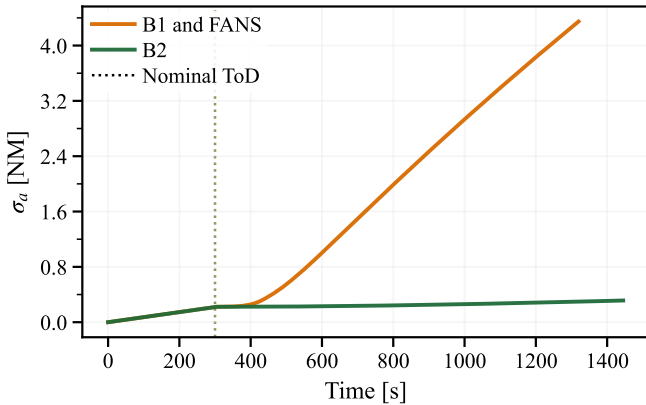


Figure 10. One standard deviation along-track uncertainty for the reference descent from FL380 to FL110.

To evaluate the Gaussian approximation used for the along-track uncertainty, the simulated along-track deviation from the nominal 270 [kt] descent was compared with the deviation implied by the Gaussian standard deviation model. The results are shown in Figure 11. The difference between the simulated and Gaussian-implied deviations increases for speed branches further away from the nominal descent speed. The largest differences occur for the outer speed branches.

For lower than nominal CAS values, the Gaussian approximation gives a smaller along-track deviation than the

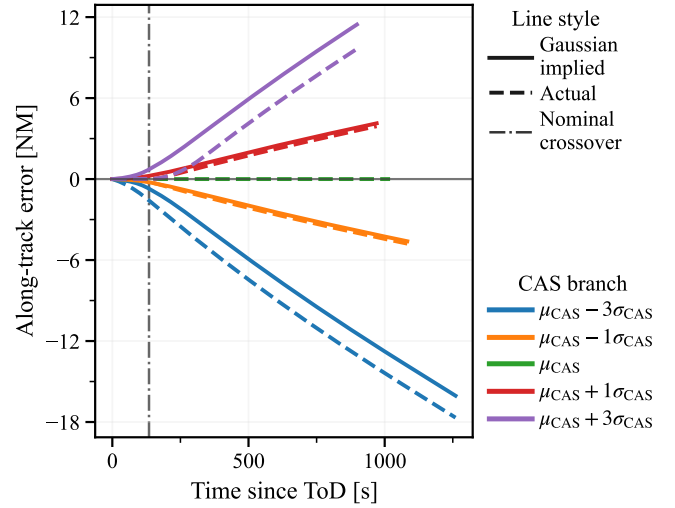


Figure 11. Gaussian approximation of along-track descent speed uncertainty for selected CAS branches.

simulated trajectory spread. For the slowest descent speed, corresponding to the three standard deviation lower branch, the simulated along-track error starts to increase from the beginning of the descent because the crossover altitude lies above the cruise altitude. The Gaussian approximation underestimates this error during the descent, resulting in an underestimation of approximately 1.5 [NM] at FL110.

For higher than nominal CAS values, the simulated along-track error remains zero for a short period because the crossover altitude has not yet been reached. In contrast, the Gaussian-implied deviation already shows an along-track error during this interval. For the three standard deviation higher branch, the final difference between the simulated and Gaussian-implied along-track deviation is approximately 1.8 [NM]. For speed branches closer to the nominal descent speed, such as the one standard deviation cases, the differences are smaller. At the end of the descent, the deviation is approximately 0.2 [NM] for both the lower and higher one standard deviation branches.

B. Conflict Probability Threshold Selection

The conflict probability threshold determines when the probabilistic CD&R logic triggers. Figure 12 summarises the paired sensitivity relative to the selected $P_{C,thr} = 10\%$ threshold. Each marker represents one density–composition scenario. For accepted trajectory adjustments and residual LoS, the markers show the median and mean paired change, respectively, relative to the same scenario at 10%.

Accepted trajectory adjustments decrease as the threshold is increased. Lower thresholds therefore impose a larger intervention burden, while the 15% and 20% thresholds reduce accepted updates relative to the selected threshold. The residual LoS response shows no consistent trend across the nine scenarios, and the apparent benefit of moving from 10% to 15% is scenario dependent. The threshold study therefore does not identify a clear empirical optimum. The value $P_{C,thr} = 10\%$ is retained as a nominal calibration point, because it reduces intervention demand relative to lower thresholds while avoiding the more permissive conflict trigger associated with higher thresholds.

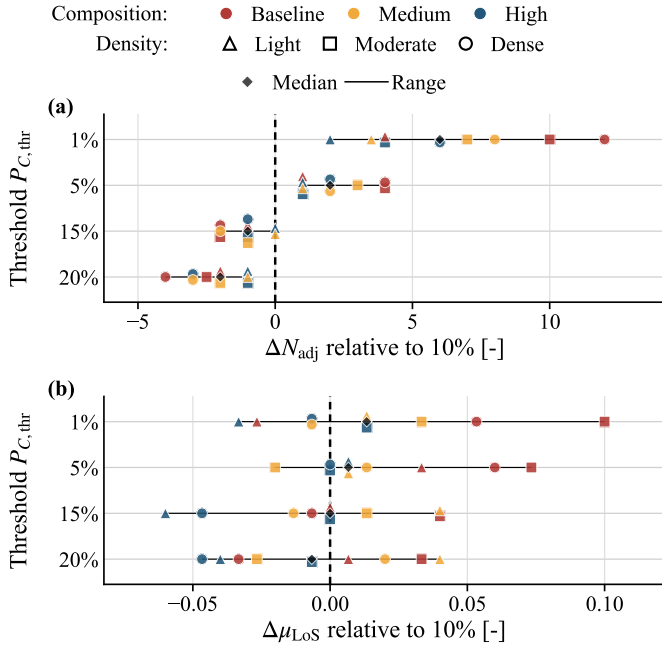


Figure 12. Paired threshold sensitivity relative to $P_{C,thr} = 10\%$ by traffic-density scenario and capability composition.

C. Conflict Management Performance

Conflict management performance is first assessed through the number of accepted trajectory adjustments, which indicates how often the strategic CD&R process modifies aircraft trajectories. Figure 13 shows this intervention demand for each traffic-density scenario and capability composition.

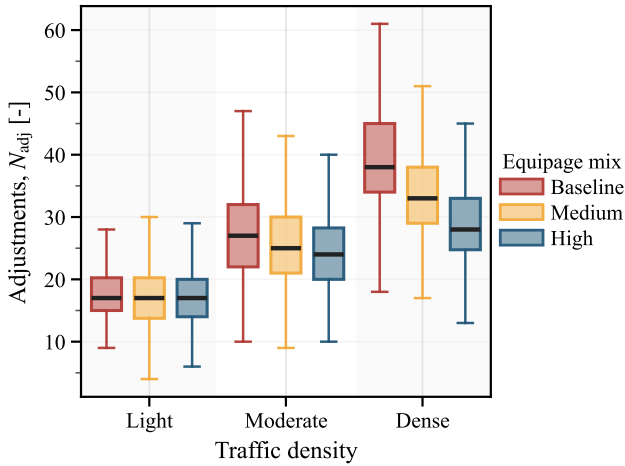


Figure 13. Accepted trajectory adjustments per Monte Carlo run by traffic-density scenario and capability composition.

Across moderate and high traffic densities, the number of accepted adjustments decreases as functional capability increases. The reduction is most pronounced in the dense traffic scenario, where the baseline composition requires the largest number of interventions. Across capability compositions, accepted adjustments increase with traffic density. Within each traffic-density scenario, the distributional spread remains broadly comparable across capability compositions. The capability effect therefore

appears mainly as a lower central tendency, rather than as a reduction in variability.

The paired Page's test in Table VII evaluates whether this visual reduction follows the expected ordered trend within each traffic-density scenario.

Table VII
PAGE'S TEST FOR ACCEPTED TRAJECTORY ADJUSTMENTS BY TRAFFIC-DENSITY SCENARIO. THE PAIRED DIFFERENCE IS DEFINED AS
 $\Delta N_{adj} = N_{adj,High} - N_{adj,Baseline}$.

Traffic density	p_{Page}	ΔN_{adj} [95% CI]	High < Baseline [%]
Light	0.029	-1 [-1, 0]	51
Moderate	< 0.001	-3 [-5, -2]	61
Dense	< 0.001	-10 [-12, -9]	86.7

The ordered reduction is statistically significant in all scenarios, although the light scenario shows only a small paired improvement, consistent with the limited separation between the boxplots. In the moderate and dense scenarios, the paired effect size increases, indicating a clearer reduction in accepted trajectory adjustments as functional capability increases.

In addition to the number of accepted adjustments, Figure 14 shows the composition of accepted trajectory management actions. Conflict speed denotes speed-only updates, whereas level-off and lateral actions may include an accompanying speed change.

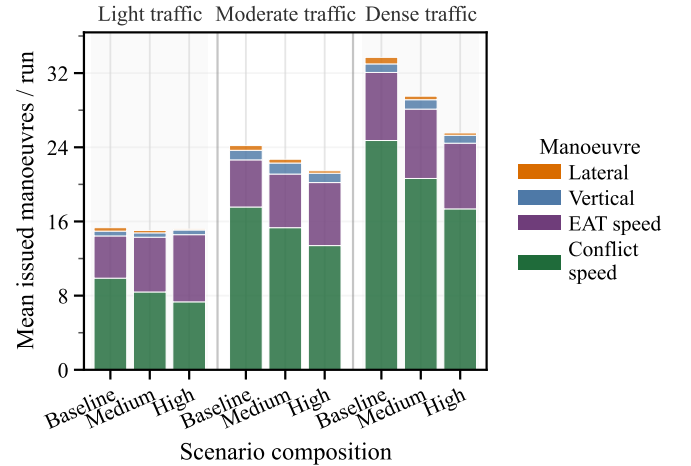


Figure 14. Mean accepted trajectory management actions per Monte Carlo run by traffic-density scenario, capability composition, and manoeuvre type.

Conflict speed updates account for most accepted actions, while level-off and lateral instructions are issued much less frequently. The figure separates conflict-related speed updates from EAT speed corrections, which are issued for arrival time adherence outside an active threshold-exceeding conflict. During conflict resolution, EAT adherence can still influence speed candidate selection as a secondary objective. As functional capability increases, the conflict-related adjustments decrease, while EAT speed corrections remain present and either stay approximately constant or increase.

After the accepted trajectory adjustments, residual separation performance is evaluated through the remaining LoS events.

Figure 15 shows the mean number of residual LoS events with 95% confidence intervals. Across all tested scenarios, the absolute number of residual LoS events remains small, indicating that residual separation losses are sparse after trajectory management. The residual LoS level is higher in the moderate and dense scenarios than in the light scenario, but does not increase monotonically between moderate and dense traffic for all capability compositions.

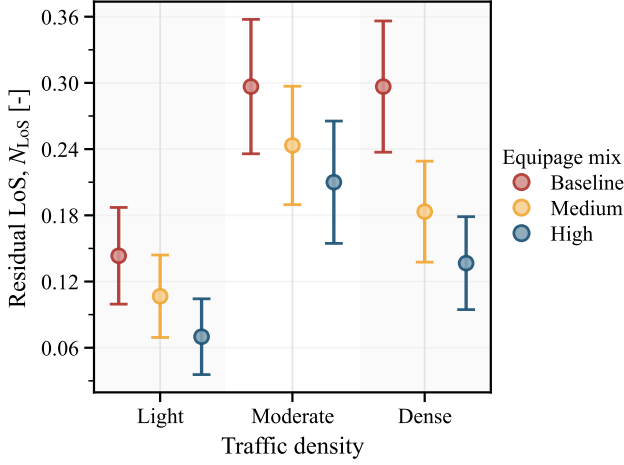


Figure 15. Mean residual LoS events per Monte Carlo run by traffic-density scenario and capability composition.

In all traffic-density scenarios, the mean number of residual LoS events decreases as functional capability increases. The reduction is smallest in the light scenario and most pronounced in the dense scenario. Although the dense scenario requires substantially more accepted trajectory adjustments than the moderate scenario, this is not reflected in a higher residual LoS count. The residual LoS results therefore indicate that the equipage-composition effect is strongest in the dense scenario.

Because residual LoS events are sparse, Table VIII reports paired outcomes relative to the baseline capability composition for common Monte Carlo seeds. Most paired runs have equal residual LoS counts. Where differences occur, higher capability more often reduces than increases the number of residual LoS events. The average LoS changes are negative in all comparisons, although the magnitudes remain small.

Table VIII
PAIRED RESIDUAL LoS OUTCOMES RELATIVE TO THE BASELINE CAPABILITY COMPOSITION FOR COMMON MONTE CARLO SEEDS.

Scenario	Capability	Fewer than baseline [%]	Equal to baseline [%]	More than baseline [%]	Average LoS change [-]
Light	Medium	9.7	83.7	6.7	-0.04
	High	12.3	82.7	5.0	-0.07
Moderate	Medium	15.7	72.7	11.7	-0.05
	High	20.3	67.0	12.7	-0.09
Dense	Medium	18.7	72.3	9.0	-0.11
	High	23.7	66.7	9.7	-0.16

D. Operational Efficiency and Arrival Timing

The operational efficiency results are reported per aircraft and centred relative to the median of the baseline capability

composition within each traffic-density scenario. Figure 16 first shows the resulting changes in flown track distance above FL110.

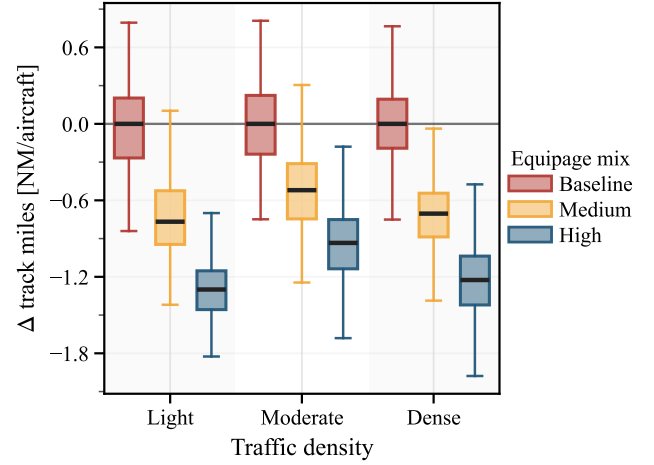


Figure 16. Flown track distance per aircraft above FL110 relative to the baseline capability median.

The medium and high capability compositions reduce flown track distance relative to the baseline composition in each traffic-density scenario. The ordering is consistent across the scenarios, with the high capability composition giving the largest reduction and the medium capability composition remaining between the baseline and high capability cases.

The paired Page's test in Table IX confirms that the ordered reduction is statistically significant in all traffic-density scenarios. The high capability composition gives a lower paired track distance than the baseline in every Monte Carlo seed, supporting the trend visible in Figure 16, although the absolute reductions remain small.

Table IX
PAGE'S TEST FOR FLOWN TRACK DISTANCE ABOVE FL110 BY TRAFFIC-DENSITY SCENARIO. THE PAIRED DIFFERENCE IS DEFINED AS
 $\Delta D_{\text{track}} = D_{\text{track,High}} - D_{\text{track,Baseline}}$

Traffic density	p_{Page}	ΔD_{track} [NM, 95% CI]	High < Baseline [%]
Light	< 0.001	-1.3 [-1.3, -1.2]	100
Moderate	< 0.001	-0.9 [-0.9, -0.9]	100
Dense	< 0.001	-1.2 [-1.3, -1.2]	100

The next operational efficiency indicator is the cumulative work above FL110, shown in Figure 17. The same general direction is visible as for flown track distance, with cumulative work decreasing as more advanced equipage becomes available. However, the differences are small across all traffic-density scenarios. The work results therefore indicate only a limited reduction over the evaluated trajectory above FL110.

The paired Page's test in Table X confirms that the ordered reduction in cumulative work is statistically significant in all traffic-density scenarios. The high capability composition gives lower paired cumulative work than the baseline in most Monte Carlo seeds, although not in every seed as observed for flown track distance. The result therefore supports a systematic reduction in cumulative work, while the altitude band decomposition below shows where this reduction occurs.

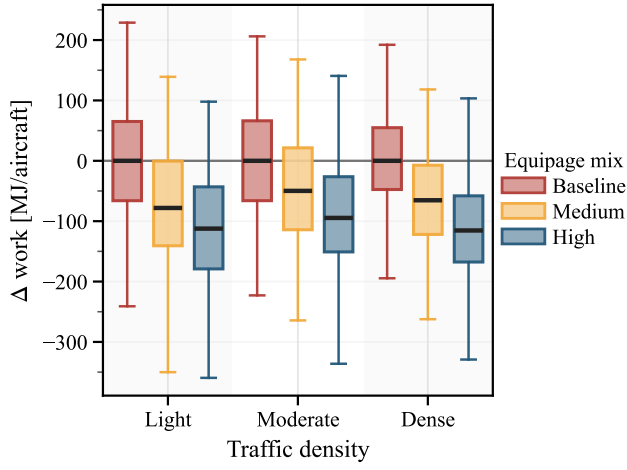


Figure 17. Cumulative work per aircraft above FL110 relative to the baseline capability median.

Table X
PAGE'S TEST FOR CUMULATIVE WORK ABOVE FL110 BY TRAFFIC-DENSITY SCENARIO. THE PAIRED DIFFERENCE IS DEFINED AS $\Delta \bar{J}_W = \bar{J}_{W,High} - \bar{J}_{W,Baseline}$.

Traffic density	p_{Page}	$\Delta \bar{J}_W$ [MJ, 95% CI]	High < Baseline [%]
Light	< 0.001	-118.1 [-123.4, -108.5]	98
Moderate	< 0.001	-87.9 [-96.1, -81.7]	96.3
Dense	< 0.001	-111.7 [-118.7, -108.3]	99.3

The altitude band decomposition in Figure 18 shows where the reduction in cumulative work occurs. Across the evaluated trajectory above FL110, the savings relative to the baseline composition remain small, ranging from approximately 0.3% to 0.6%.

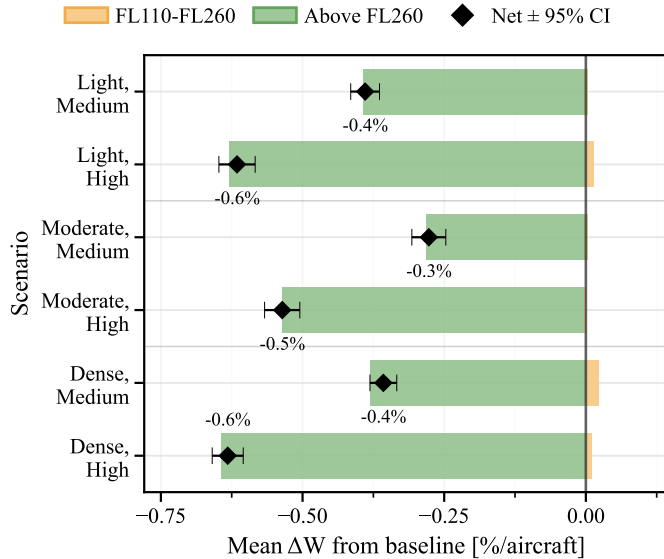


Figure 18. Cumulative work change per aircraft relative to the baseline capability, decomposed by altitude band.

In Figure 18, the same ordering as in Figure 17 is visible, but the reduction is mainly located above FL260, outside the ACC

control volume considered for conflict management. Within the FL110–FL260 band, the reductions remain comparatively small.

1) *EAT adherence*: The arrival time results are summarised in Table XI. Across the tested scenarios, EAT performance remains broadly comparable across capability compositions, indicating that the reduction in conflict management interventions does not substantially alter arrival time adherence.

Table XI
EAT PERFORMANCE BY TRAFFIC-DENSITY SCENARIO AND CAPABILITY COMPOSITION. THE SIGNED ERROR IS DEFINED AS $e_{EAT} = t_{IAF} - EAT$.

Scenario	Metric	Baseline capability	Medium capability	High capability
Light	within tolerance [%]	81	79	76
	median e_{EAT} [s]	33	30	34
	mean $ e_{EAT} $ [s]	77	79	82
Moderate	within tolerance [%]	63	63	63
	median e_{EAT} [s]	86	84	84
	mean $ e_{EAT} $ [s]	112	110	110
Dense	within tolerance [%]	69	69	68
	median e_{EAT} [s]	55	53	53
	mean $ e_{EAT} $ [s]	98	97	97

VI. DISCUSSION

This section interprets the results in relation to the hypotheses and the modelling assumptions of the experiment. The discussion first considers conflict management performance and the interpretation of residual LoS, followed by the efficiency effects, EAT adherence, and the role of the uncertainty model. The section concludes by identifying the main limitations and directions for future work.

A. Conflict Management Interpretation

The accepted-adjustment results support *H1*. Increasing functional capability reduces the number of trajectory modifications required after the initial prediction phase, but the operational magnitude depends on the traffic sample. In light traffic, the number of accepted adjustments is already low and the difference between capability compositions remains small. In moderate and dense traffic, more encounters reach the conflict detection threshold, so improved intent access has more opportunity to reduce the number of required trajectory modifications.

The action composition shows that the effect is not only a reduction in conflict resolution work, but also a change in the type of trajectory management workload. Conflict-related speed commands decrease with increasing capability, while EAT-only commands become more prominent. These EAT-only commands are issued outside active threshold-exceeding conflicts and therefore represent timing management work rather than separation assurance work. The result should therefore be interpreted as a shift in workload composition: fewer trajectories require conflict resolution commands, while some still require speed corrections to maintain the assigned arrival time.

The residual LoS results support *H2* in a conservative sense. Residual events remain sparse after CD&R, and the paired comparison shows that higher capability does not systematically increase residual risk. Most paired runs have equal residual

LoS counts, while the average changes are slightly negative for the higher capability compositions. The metric therefore represents a post-resolution risk outcome inside the evaluated FL110–FL260 domain, not the underlying conflict exposure itself. This distinction is important because the dense scenario requires substantially more accepted trajectory adjustments than the moderate scenario, while the counted residual LoS level does not increase accordingly. Operationally, the result suggests reduced residual conflict burden within the strategic CD&R phase, but not a removal of residual risk.

Within each traffic-density scenario, the pattern remains consistent with the equipage hypothesis: higher capability compositions produce fewer residual LoS episodes than lower capability compositions. The weaker density ordering should be read as a consequence of the specific interactions that remain after trajectory management, rather than as a direct function of aircraft count alone. This interpretation is also limited by the use of three selected traffic samples, so the stronger reduction in the dense scenario should not be read as a general statistical relation between density and residual LoS reduction. These interactions are shaped by the traffic sample, route geometry, upper airspace delivery conditions, and the sequential nature of the CD&R process. A resolution accepted for one conflict changes the subsequent trajectory geometry and can therefore remove, shift, or introduce later interactions in the remaining conflict set. This is operationally plausible for sectors 1 and 2, where inbound traffic converges towards ARTIP and restricted airspace within the Dutch FIR constrains routing near the sector boundary.

B. Operational Efficiency Interpretation

The efficiency results support *H3* at the level of the evaluated trajectory above FL110. Page’s tests confirm statistically supported ordered reductions in both flown track distance and cumulative modelled work with increasing functional capability. The location of the work reduction remains important: most of the saving is observed above FL260, while the contribution inside FL110–FL260 is small and not uniformly negative.

Flown track distance and cumulative work do not vary in direct proportion. The reduction in flown track distance is partly linked to the equipage-dependent route representation, because more capable aircraft can use more flexible coordinate-based routing than ATN B1 aircraft. Modelled work, however, also depends on speed changes, vertical manoeuvres, thrust demand, and the mix between inbound and outbound traffic. This is consistent with the accepted action composition: conflict-related speed commands decrease with increasing capability, while vertical resolutions remain broadly comparable and EAT-only speed corrections become more prominent. Under fixed FPA descent, such speed corrections can affect arrival energy development without producing an equivalent change in flown track distance.

This pattern is partly shaped by the fixed FPA descent model. The distance required to descend through a fixed altitude interval is proportional to the altitude loss and inversely related to the tangent of the descent angle. Under this assumption, upstream route shortening does not necessarily reduce the distance flown inside the ACC altitude band. It can instead reduce the path

flown before the aircraft enters that band, while the descent distance inside the band remains mainly determined by the vertical interval and the selected descent angle.

The altitude band result is therefore not a uniform efficiency gain throughout Amsterdam ACC. Improved equipage reduces trajectory inefficiency over the evaluated trajectory, but the main work reduction occurs outside the FL110–FL260 conflict management domain. The contribution within the domain is small and does not show a consistent benefit across all tested conditions. Operationally, part of the benefit therefore depends on whether adjacent and upper airspace can support the same trajectory-based coordination concept. If neighbouring sectors cannot accommodate the upstream route changes, the savings observed above FL260 may not fully translate into benefit inside Amsterdam ACC.

The limited work effect within the domain should therefore be interpreted cautiously. The evaluated FL110–FL260 band contains both inbound and outbound traffic, different resolution types, and trajectory changes that may affect work in different directions. Consequently, the work result within the domain does not isolate one physical mechanism. It mainly shows that the aggregate efficiency benefit observed over the evaluated trajectory is not concentrated inside the Amsterdam ACC conflict management domain.

C. Influence on Arrival Time Management

The EAT results mainly serve as a comparability check. Across the tested scenarios, adherence rate, median signed error, and mean absolute error remain comparable between equipage compositions. The reduction in accepted adjustments and the efficiency effects are therefore not obtained by allowing worse arrival time performance.

This interpretation is bounded by the scenario construction. The assigned EATs were made reachable for the nominal trajectories of each equipage class. The results therefore do not show that higher capability aircraft can always absorb the same arrival time targets in operation. It shows that, under a feasible and controlled EAT assignment, no clear degradation in EAT performance is observed when capability increases.

This distinction matters for implementation. More capable aircraft may fly shorter or more direct routes. If the same EAT is retained, these aircraft may require additional speed reduction, upstream delay absorption, or a revised arrival time assignment. The increase in EAT-only speed corrections is consistent with this interpretation: route flexibility can create a timing management requirement even when no active conflict is predicted.

D. Interpretation under the Uncertainty Model

The conflict management results are conditional on the uncertainty model used to activate CD&R. Since conflicts are detected through a probability threshold, the assumed trajectory error distribution influences which encounters reach the resolution stage. The uncertainty model is therefore part of the experimental treatment, rather than only a numerical implementation detail.

The vertical uncertainty around the descent angle is conservative near ToD. A symmetric Gaussian representation can

overestimate vertical spread because the aircraft is bounded by the cruise level before descent begins. In the evaluated scenarios, this effect is limited by the scenario construction: aircraft are spawned sufficiently high relative to the control volume, so most of this overestimation occurs before the region in which the performance metrics are evaluated.

Along-track uncertainty is particularly relevant for conflict management because it affects when an aircraft is expected to reach a potential conflict area. If the model predicts an aircraft to arrive too early or too late at such a point, the estimated interaction with other traffic may shift as well. The validation showed that the Gaussian approximation slightly underestimates this effect for slower descent speed branches, mainly in the outer speed cases. Around the nominal descent speed range, the difference remains small. These approximation errors could affect individual encounters close to the probability threshold, but they are not expected to change the scenario-level trends.

The model also excludes several operational sources of trajectory prediction uncertainty. Pilot response, communication latency, controller timing, aircraft performance modelling error, and weather-related prediction error besides wind are not represented explicitly. The results should therefore be read as the outcome of a controlled equipage-comparison model, not as a complete representation of operational trajectory uncertainty.

E. Limitations and Future Work

The study is a controlled trajectory management experiment. Fixed traffic samples, aircraft performance assumptions, conflict detection logic, resolution options, and arrival time constraints isolate the effect of functional equipage capability. This supports a controlled comparison between equipage compositions, but it also limits generalisation to the full operational environment around Amsterdam ACC.

Future work should reduce the asymmetry between inbound and outbound trajectory modelling. Inbound intent uncertainty is represented through descent angle and descent speed, whereas outbound uncertainty is limited mainly to execution effects. Including uncertainty in climb speed, climb profile, route execution, and altitude constraints would provide a more balanced assessment of mixed inbound–outbound operations.

The fixed FPA descent assumption should also be treated as an operational simplification. It provides a prescribed vertical geometry for comparing equipage compositions, but current operations contain idle descents, step descents, speed-managed descents, and mixed vertical profiles. Forcing all aircraft into a single fixed FPA concept could be difficult operationally and could itself change the traffic management problem. Future work should test whether the observed equipage effects remain when vertical profiles are sampled from operational descent behaviour rather than imposed through a single fixed FPA model.

The airspace scope should be expanded above and adjacent to Amsterdam ACC sectors 1 and 2. The results indicate that part of the efficiency benefit occurs above FL260, outside the conflict management volume considered here. A larger model should include adjacent and upper airspace, the delivery of arrival flows into Amsterdam ACC, and coordination with neighbouring ANSPs. Application to other Dutch sectors or airport environments should also be tested. This would show

whether upstream trajectory savings can be converted into local operational benefit, or whether they are absorbed by downstream convergence and sequencing constraints.

Finally, the resolution and scenario models should be broadened. The current resolution set captures a limited set of speed, lateral, and vertical trajectory modifications. Operational conflict management also includes more flexible vectoring, holding, altitude coordination, and sequencing actions. Future equipage scenarios should account for fleet evolution as well, since increasing availability of ADS-C and FMS-integrated CPDLC may coincide with changes in aircraft type, performance, and preferred descent behaviour.

VII. CONCLUSION

This study assessed how increasing ADS-C and CPDLC capability affects conflict management and operational efficiency in a partial trajectory-based operations model for Amsterdam ACC airspace. The model combines mixed inbound and outbound traffic, equipage-dependent intent availability, probabilistic CD&R, and Monte Carlo sampling of wind field mismatch and arrival intent. This evaluates the effect of mixed equipage conditions on partial TBO performance in the selected operational domain.

The results show an ordered reduction in accepted trajectory adjustments as functional capability increases. This effect is limited in light traffic, but becomes clearer under moderate and dense traffic demand. Residual LoS remains sparse across all compositions, with no indication that the reduction in trajectory adjustments compromises separation performance. Higher capability therefore reduces trajectory management demand while maintaining residual LoS performance in the evaluated scenarios.

Operational efficiency also improves over the evaluated trajectories above FL110. Increasing capability reduces flown track distance and cumulative work, while EAT adherence remains comparable across equipage compositions. The cumulative work reduction is mainly located above FL260, and is therefore largely outside the Amsterdam ACC conflict management volume considered in this study.

Overall, the results indicate that increased access to aircraft intent and more flexible CPDLC-enabled trajectory update options improve partial TBO performance under mixed equipage conditions. Future work should extend the uncertainty model, especially for outbound traffic and operational execution uncertainty, and evaluate the framework over adjacent and upper airspace to assess how the observed benefits propagate beyond the Amsterdam ACC control volume.

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Part B

Literature Review & Research Definition

Airspace Design

The first step to define an ATM model is to understand the airspace structure in which it operates. This chapter provides an overview of the Dutch airspace design. First, the general layout of the airspace is described in Section 2.1. Next, part of this airspace and its control centre, the Amsterdam ACC is explained in more detail in Section 2.2.

2.1. General Layout

The Amsterdam Advanced ATC (AAA) system structures the Dutch Flight Information Region (FIR) into a layered control environment, illustrated in Figure 2.1. Tower control manages the Control Region (CTR), Approach Control (APP) manages the Terminal Maneuvering Area (TMA), and Amsterdam ACC manages the Control Area (CTA). Above the Amsterdam ACC control domain, upper airspace is delegated to Eurocontrol's Maastricht Upper Area Control (MUAC) in the Upper Control Area (UTA). This organisation provides a continuous chain of responsibility from surface movement to upper airspace and back to the terminal environment.

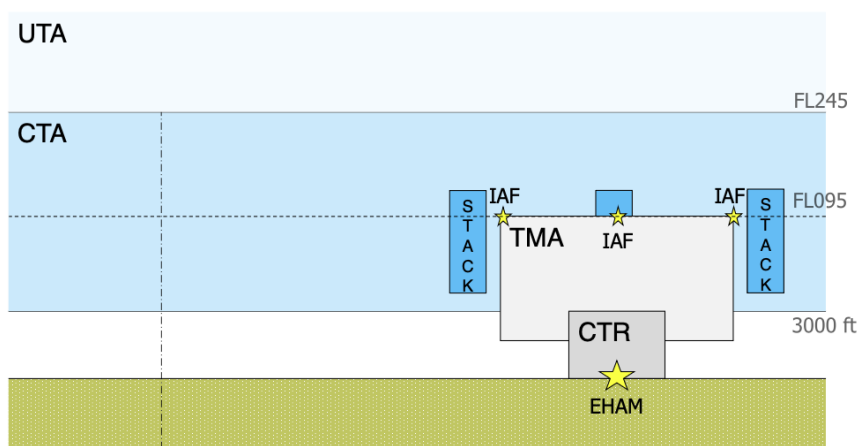


Figure 2.1: Schematic representation of controlled airspace in the Netherlands [1].

The control sequence follows the vertical and procedural structure of the airspace. Departing aircraft are first handled by tower control for surface movement and take-off, then by APP during the initial climb through the terminal area, and subsequently by Amsterdam ACC during the transition into the en route environment. Aircraft climbing above the Amsterdam ACC domain are transferred to MUAC. For arrivals, the process is reversed: MUAC transfers aircraft to Amsterdam ACC for descent through the control area, after which APP provides terminal sequencing and approach guidance. Tower control then manages final approach, landing, and ground movement [1, 2].

Tower control is responsible for aircraft on the ground and in the immediate vicinity of the aerodrome. This includes taxiing, take-off, landing, and local traffic integration within the CTR. The CTR extends up to approximately 3000 ft (FL 30) and covers a radius of roughly 15 km around the airport.

APP manages traffic within the TMA. Its task is to organise inbound and outbound flows between the airport environment and the surrounding control area. For arrivals, this includes sequencing traffic from the Initial Approach Fix (IAF) towards the approach path. For departures, it includes guiding the initial climb and preparing the transition towards Amsterdam ACC. The Schiphol TMA extends from the lower terminal environment to approximately FL 95.

Amsterdam ACC supervises traffic in the Dutch CTA, which generally starts at FL 095. Its responsibilities include separation assurance, conflict resolution, sequencing towards the IAFs, and coordination with adjacent sectors and control centres. In regions not covered by APP, Amsterdam ACC responsibilities may extend to lower altitudes. Above FL 245, responsibility is transferred to MUAC, which manages the delegated upper airspace in the UTA. The organisation of Amsterdam ACC is discussed in more detail in Section 2.2.

2.2. Amsterdam Area Control Centre

To distribute workload in the high-density traffic environment around Schiphol, Amsterdam ACC is divided into five sectors, as shown in Figure 2.2. Sectorisation allows traffic flows to be managed by geographically and vertically bounded controller positions while maintaining coordination across the wider Dutch FIR.

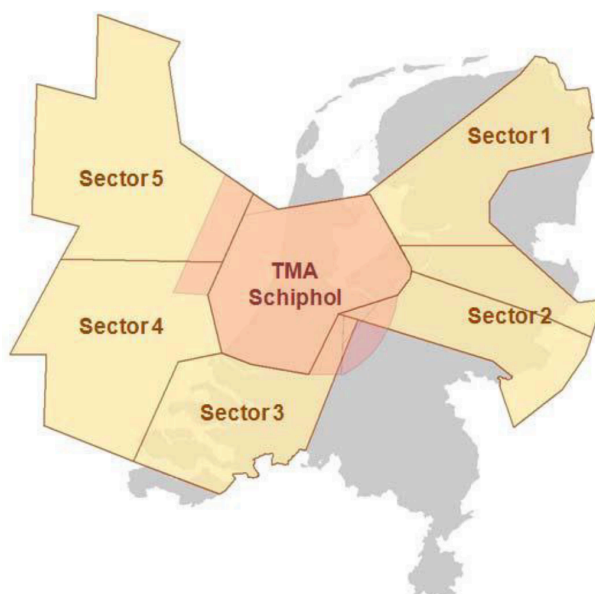


Figure 2.2: Five sectors in which Amsterdam ACC is divided [3].

Within this sectorised airspace, Amsterdam ACC is responsible for separation assurance, conflict resolution, sequencing towards arrival fixes, and coordination with adjacent units. The operational task is therefore not limited to maintaining separation between individual aircraft, but also includes shaping inbound and outbound flows so that they remain compatible with downstream sector capacity and terminal area constraints.

Schiphol arrival traffic is structured through Standard Arrival Routes (STARs), which converge towards the IAFs at the interface with the Schiphol TMA. The three principal IAFs are SUGOL in the west, RIVER in the south, and ARTIP in the east. These fixes provide the main delivery points for inbound traffic and may also be used for holding when traffic demand exceeds the available arrival capacity. An overview of the STARs into Schiphol is provided in Figure 2.3.

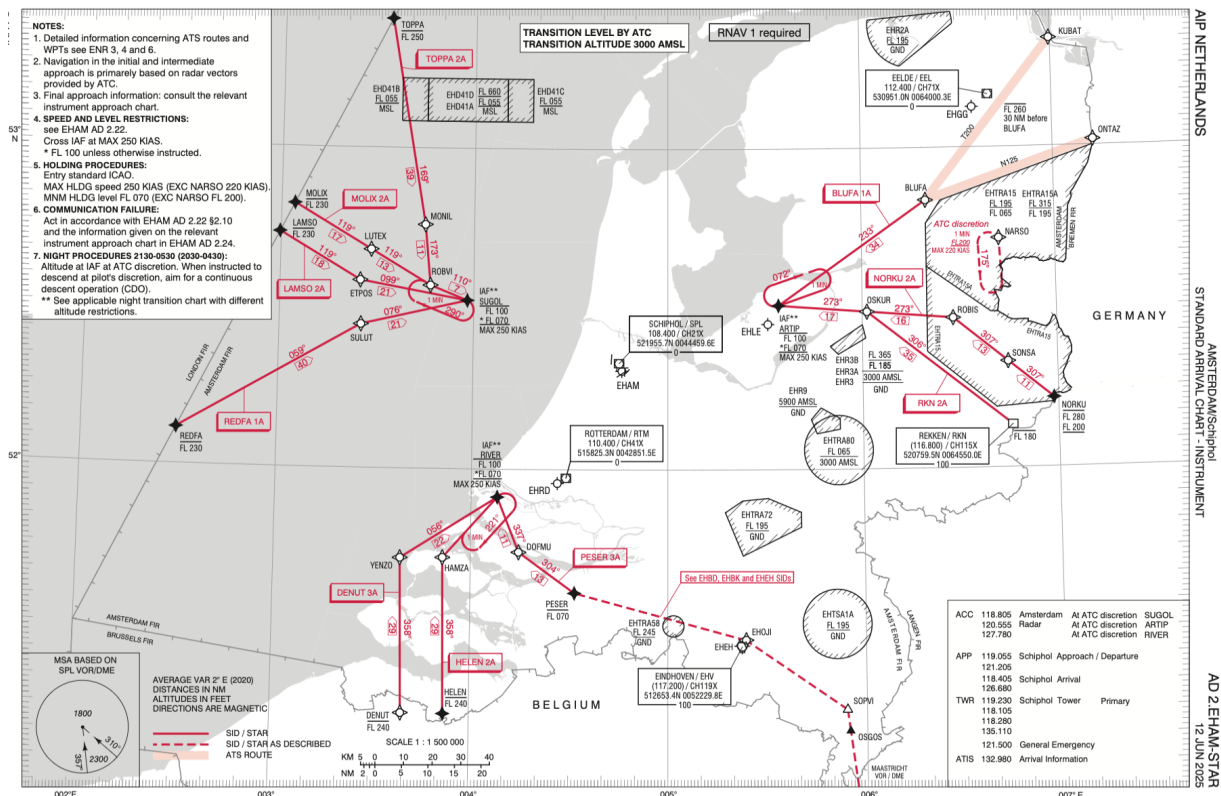


Figure 2.3: STARs into Schiphol TMA [4].

Operationally, Amsterdam ACC aims to deliver each aircraft to the appropriate arrival fix safely, in the correct sequence, and within a tolerance of 120 s of the Expected Approach Time (EAT), which is typically assigned by a planner. Controllers achieve this by merging flows from multiple FIR boundaries and by applying tactical measures such as vectors, altitude clearances, and speed adjustments. These interventions maintain separation while also forming the arrival sequence required by the terminal area.

Although STARs provide the nominal structure for inbound traffic, controllers retain tactical flexibility. When traffic conditions and coordination allow, aircraft may receive shortcuts or direct routings that deviate from the published STARs. In some cases, coordination with APP may also allow aircraft to enter the terminal area through a point other than the standard IAF. Runway allocation is an important driver of these deviations, because the preferred terminal entry point depends on the active arrival configuration.

Outbound Schiphol traffic is initially structured through Standard Instrument Departures (SIDs), which define the lateral routing and initial climb constraints associated with each runway configuration. These procedures provide predictability close to the airport, but generally terminate near or just above FL 090. Amsterdam ACC is therefore responsible for managing the continuation of the climb and the transition towards the en route structure. This includes assigning suitable routings, issuing direct clearances where appropriate, and accounting for restricted airspace and military training areas. The SIDs departing Schiphol are shown in Figure 2.4.

In addition to Schiphol inbounds and outbounds, Amsterdam ACC also manages overflights and regional traffic to and from airports such as Rotterdam, Eindhoven, Brussels, and Düsseldorf. This mixture of arrival, departure, overflight, and regional flows makes the Amsterdam ACC environment operationally complex and creates a need for continuous coordination between sectors and neighbouring control units [2].

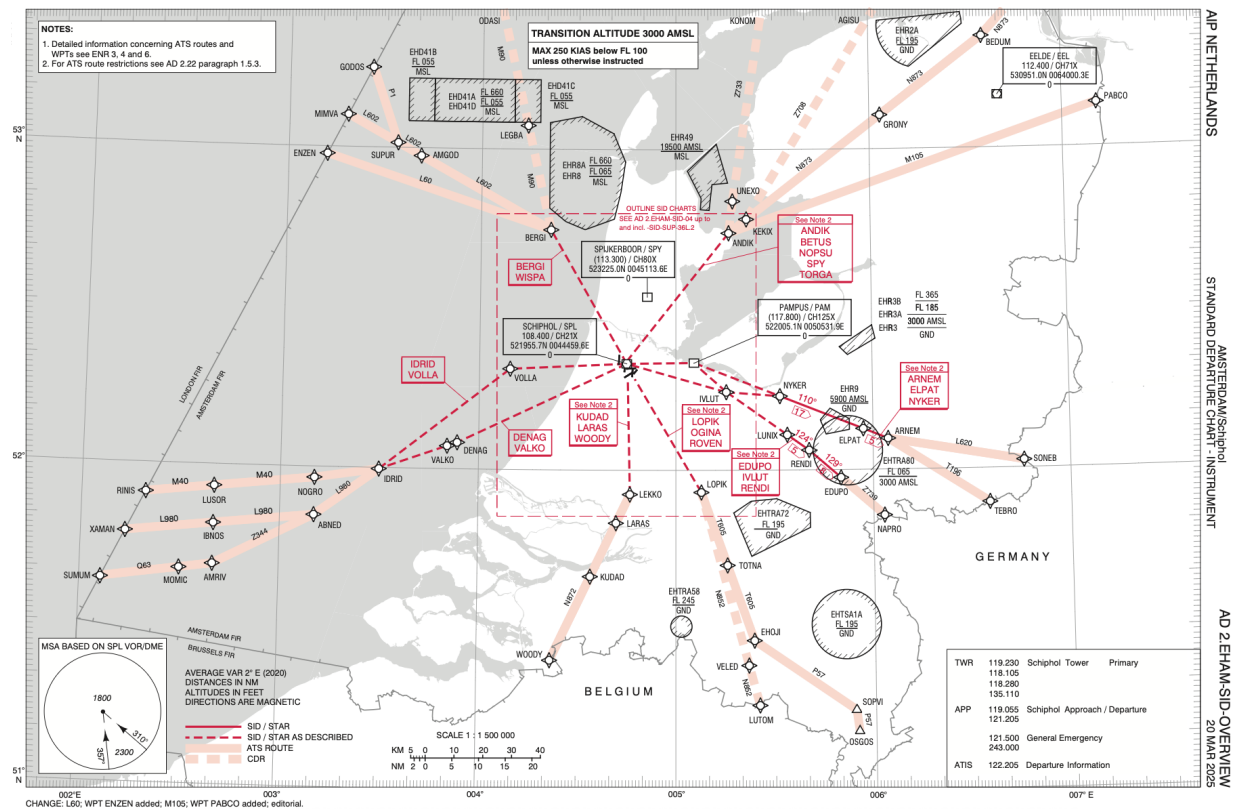


Figure 2.4: SIDs out of Schiphol [5].

Communication and Surveillance

Communication and surveillance form the operational backbone of ATM. Communication enables the exchange of clearances, instructions, and updates between controllers and flight crews, while surveillance provides the positional awareness required to ensure safe separation and manage traffic flow. This chapter outlines the key technologies supporting these functions in modern ATM. Section 3.1 introduces conventional voice communication, followed by Automatic Dependent Surveillance–Contract (ADS-C) in Section 3.2. Section 3.3 discusses Controller–Pilot Data Link Communications (CPDLC), and Section 3.4 concludes with an overview of Automatic Dependent Surveillance–Broadcast (ADS-B).

3.1. Voice Communication

The primary means of interaction between air traffic controllers and pilots remains voice communication. It enables real-time exchange of clearances, instructions, and situational updates. In continental airspace, voice communication is typically facilitated via Very High Frequency (VHF), while High Frequency (HF) is employed in oceanic and remote regions where line-of-sight transmission is not feasible. To mitigate ambiguity, standardised International Civil Aviation Organization (ICAO) phraseology is prescribed. However, operational challenges persist. Frequency congestion, overlapping transmissions, phraseology deviations, and language-related misunderstandings can contribute to communication errors and increased controller workload [6, 7].

These limitations not only affect safety and efficiency, but also constrain the ability to support more advanced modes of operation. Despite its importance to current operations, voice communication is inherently unstructured and not machine-readable. This limits its integration with automated trajectory management systems. The absence of formalised data structures hinders the consistent interpretation of instructions and delays the execution of trajectory updates, introducing uncertainty into aircraft intent and conformance [7, 8].

3.2. Automatic Dependent Surveillance–Contract

Developed to extend surveillance coverage beyond the limits of radar infrastructure, ADS-C enables aircraft to automatically downlink position and intent information to the appropriate Air Traffic Service Unit (ATSU). In addition to reducing reliance on voice-based position reports, ADS-C facilitates the application of reduced separation standards by providing more timely, structured, and accurate aircraft state data [6, 7].

Information exchange under ADS-C is governed by surveillance contracts established between the aircraft and the receiving ATSU. These contracts define the conditions under which specific data are transmitted, including position, altitude, velocity, intent information, and selected meteorological parameters. The data is derived from onboard navigation systems and the Flight Management System (FMS). Three contract types are commonly used [6, 7]:

- **Periodic contract:** data is transmitted at regular, predefined time intervals.
- **Demand contract:** a one-time report is requested by the ATSU, without altering existing contracts.
- **Event contract:** a report is automatically triggered by specific events, such as waypoint change events, lateral deviation events, or level range deviation events.

Multiple contracts can be active simultaneously for the same aircraft, provided each is of a distinct type. While ADS-C significantly improves surveillance coverage beyond radar range, it does not deliver continuous updates. Instead, the timeliness and frequency of reports are constrained by the parameters defined within the active contracts.

3.2.1. Future Air Navigation System 1/A

The first large-scale operational deployment of ADS-C occurred with the introduction of the FANS concept in the early 1990s. FANS 1, developed by Boeing, and FANS A, developed by Airbus, were collectively implemented as FANS 1/A [6, 9]. This system combined CPDLC for digital controller–pilot communication with ADS-C for surveillance. Both applications operated over the Aircraft Communications Addressing and Reporting System (ACARS) network, using satellite, HF, or VHF links as the primary communication means.

Within FANS 1/A, ADS-C reports were organised into predefined data groups. The basic group, always included in each report, contained latitude, longitude, altitude, a timestamp, and a figure of merit indicating navigational accuracy. Optional groups could be appended depending on the contract parameters, including intent, speed, vertical rate, meteorological data, and aircraft identification. Especially relevant was the Intermediate Projected Intent (IPI) group, which enabled the downlink of up to ten Trajectory Change Points (TCPs) generated by the onboard FMS. Each TCP lay between the aircraft's current position and a fixed projected point and represented a planned change in altitude, speed, or lateral route which typically includes key points such as the Top of Descent (ToD). The IPI group therefore provided a structured but limited view of the aircraft's intent [6, 7].

FANS 1/A enabled non-radar surveillance in remote regions and reduced reliance on manual voice position reports. However, its effectiveness was limited by the low bandwidth of the ACARS network and the constrained structure of ADS-C messages [6, 9].

3.2.2. Aeronautical Telecommunication Network Baseline 1

To address limitations in earlier data link implementations, the ICAO developed the Aeronautical Telecommunication Network (ATN) in the late 2000s as a globally standardised framework for air–ground data link communication. The first formal baseline, ATN B1, introduced a harmonised infrastructure to ensure interoperability between airborne and ground systems across different regions and manufacturers [6, 7].

The ATN B1 baseline supports a defined set of Aeronautical Telecommunication Services (ATS), commonly referred to as ATS B1, centred on digital controller–pilot communication and associated context management functions. In contrast to the bandwidth-limited ACARS network used under FANS 1/A, communication under ATN B1 is primarily conducted via the VHF Data Link Mode 2 network, providing increased capacity, reduced latency, and improved reliability for continental operations [6, 7].

Within the ATN B1 capability set, ADS-C is not supported and no ADS-C-based downlink of trajectory intent information is available [7]. As a result, the primary operational benefit of ATN B1 lies in the structured and standardised exchange of clearances, requests, and reports through CPDLC. However, integration of uplinked messages with the onboard FMS is not mandated under this baseline. Consequently, trajectory amendments such as altitude, route, or speed changes continue to rely on manual interpretation and entry by the flight crew, introducing execution delays and limiting automation.

Overall, ATN B1 represents an important step towards global interoperability and digital communication in ATM, but it does not support automated trajectory synchronisation or intent-based operations between airborne and ground systems [6, 9].

3.2.3. Aeronautical Telecommunication Services Baseline 2

ATS B2 extends air–ground data link integration by combining structured digital communication with more detailed trajectory reporting. Its principal addition is the Extended Projected Profile (EPP), an optional ADS-C data group that downlinks the 4D reference trajectory computed by the aircraft's FMS. The EPP may contain up to 128 TCPs, each describing part of the predicted trajectory ahead of the aircraft through position, altitude, speed, time, and constraint information. Compared with the more limited IPI group used under FANS 1/A, this provides a substantially richer representation of airborne intent and supports closer synchronisation between flight deck and ground-based trajectory predictions [10]. Under the Euro-

pean regulatory framework, compliance with ATS B2 is mandated for aircraft operating above FL 285 and holding a certificate of airworthiness issued after 2027 [10].

Each EPP report describes the predicted path within a defined planning horizon. The availability and resolution of the reported information depend on the version of the onboard ADS-C application and the configuration of the active reporting contract. The following parameters may be included [10]:

- Position, expressed as latitude and longitude
- Altitude
- Waypoint name
- Estimated speed
- Estimated time
- Vertical type, such as level, climb, or descent segment
- Lateral type, such as turn, straight, or radius-to-fix segment
- Applicable level, speed, or time constraints for the TCP
- Aircraft gross mass
- Trajectory intent status, indicating the managed mode and validity of the predicted profile

The parameters contained in the EPP allow ground automation systems to reconstruct the aircraft's intended 4D trajectory and evaluate whether the downlinked trajectory remains consistent with the expected operational plan. A key operational difference with earlier baselines is the stronger coupling between data link applications and the managed trajectory in the FMS. Uplinked CPDLC clearances can be aligned with the airborne trajectory representation, while the EPP provides the corresponding downlink of the active FMS trajectory to ground systems. This improves the consistency between issued clearances, airborne execution, and ground-based prediction, which is essential for trajectory-based automation [10].

The operational relevance of EPP has been demonstrated for several trajectory-based functions. By providing ground systems with access to the active airborne trajectory, EPP can support:

- Improved Conflict Detection & Resolution (CD&R) through synchronised trajectory intent
- More accurate conformance monitoring against the managed reference profile
- Enhanced flow and capacity management through pre-tactical and tactical trajectory negotiation
- Integration with time-based operations, including Required Time of Arrival (RTA) planning and monitoring

These functions can reduce controller workload, improve arrival sequencing, and enhance predictability, particularly in mixed-equipage environments [9, 11].

However, the downlinked EPP should not be interpreted as a complete representation of aircraft intent. It reflects the active flight plan and currently cleared trajectory, meaning that tactical interventions, conditional clearances, or pending crew actions may make the data temporarily outdated. The message also does not contain all internal FMS parameters, such as airline specific cost indices, detailed fuel models, or high resolution wind information. Consequently, residual differences may remain between the airborne prediction and the trajectory reconstructed by ground-based systems [9, 11].

3.3. Controller–Pilot Data Link Communications

Digital communication between air traffic controllers and flight crews enables the exchange of structured messages, providing an asynchronous alternative to conventional voice communication. The initial deployment of CPDLC occurred under the FANS 1/A framework, primarily for oceanic and remote operations via the ACARS network. Subsequent standardisation for continental environments was achieved through ATN B1 and ATS B2, which introduced enhancements in message structuring, system interoperability, and integration with both airborne and ground-based infrastructure [6].

In contrast to voice communication, CPDLC supports the precise and unambiguous transmission of clearances, requests, and reports, thereby reducing the likelihood of misinterpretation and mitigating frequency congestion. The use of predefined, machine-readable message sets allows for automated processing at

both ends of the communication chain, ensuring consistency in the representation and execution of operational instructions.

Message exchange in CPDLC adheres to a standardised format defined by the ICAO, in which each message is assigned a unique identifier and classified as either an Uplink Message (UM), sent from controller to pilot, or a Downlink Message (DM), sent in the reverse direction. Typical examples include UM20 (CLIMB TO [level]) and DM6 (REQUEST [level]). While predefined message sets enable structured and automatable communication, limited free-text capability remains available for non-routine situations, though its use is discouraged due to incompatibility with automation. Each transaction generally follows a predictable sequence comprising the uplink, pilot response (WILCO, UNABLE, or STANDBY), and system acknowledgment, thereby ensuring traceability and enabling integration into automated workflows [8, 10].

Through its structured message format, CPDLC facilitates integration with automation on both ends of the communication link. Ground systems can correlate uplinked instructions with downlinked intent data from ADS-C and EPP to support conformance monitoring, conflict detection, and sequencing tasks. On the flight deck, contextual message display reduces cognitive load and communication error rates.

However, several limitations limit the effectiveness of CPDLC in practice. Ambiguities in open or conditional clearances introduce uncertainty into trajectory predictions, while message exchange and crew response times cause short-term deviations between predicted and actual aircraft states [8]. These effects are examined further in Chapter 5.

3.4. Automatic Dependent Surveillance – Broadcast

As a broadcast-based surveillance system, ADS-B enables aircraft to autonomously transmit their current state information to both ground receivers and nearby aircraft. Each transmission includes a unique aircraft identifier, three-dimensional position (latitude, longitude, altitude), horizontal and vertical velocity components, barometric setting, turn indication, emergency status, transponder capability, and navigation performance metrics. These data are derived from the aircraft's onboard navigation and transponder systems and are emitted continuously, without the need for interrogation. Unlike ADS-C, which relies on predefined reporting contracts with a specific ground station, ADS-B adopts an open architecture, allowing any suitably equipped receiver within range to access the information [6].

In operational terms, ADS-B contributes to enhanced situational awareness for both ground-based controllers and flight crews. It enables real-time surveillance coverage in areas where radar infrastructure is limited or unavailable, such as oceanic or low-altitude airspace. Nevertheless, the system is constrained to broadcasting the current aircraft state and does not convey future intent. As a result, ADS-B alone is insufficient for enabling TBO and must be complemented by systems such as ADS-C, which support the downlink of structured intent information from the aircraft's FMS [6].

Trajectory-Based Operations

Trajectory information plays an increasingly central role in the modernisation of ATM. As traffic density, system complexity, and environmental constraints continue to grow, future concepts rely on a more predictive, trajectory-oriented approach to managing aircraft movement. In this chapter, the concept of TBO is introduced. TBO is seen as the future of ATM. First, the context of TBO is explained in Section 4.1. Next, more details are provided on TBO itself, and the typical elements of a TBO model are described in Section 4.2. Existing research in TBO and mixed equipage is discussed in Section 4.3. Finally, the knowledge gap is identified in Section 4.4.

4.1. Context

European airspace is undergoing structural change driven by sustained traffic growth and rising operational complexity. In 2019, the network accommodated about 11 million flights, a figure projected to reach nearly 16 million annually by 2050. Meanwhile, civil airspace availability has decreased due to geopolitical constraints, and new airspace users such as unmanned systems, zero-emission aircraft, and high-altitude aircraft further increase management challenges. These developments highlight the need for a more integrated, flexible, and scalable ATM architecture [12].

The Single European Sky (SES) initiative represents Europe's coordinated response, aiming to reduce fragmentation and enhance performance through the Single European Sky ATM Research (SESAR) programme. Guided by the European ATM Master Plan, the transition toward the Digital European Sky emphasises scalability, sustainability, and cross-border interoperability [12].

In parallel, the United States pursues comparable objectives under the Next Generation Air Transportation System (NextGen) programme. Although institutional contexts differ, both initiatives converge on a trajectory-oriented, data-driven approach to ATM, supported by ICAO to promote global harmonisation [13].

4.2. Introduction to TBO

By positioning the flight trajectory as the central reference for coordination across all phases of flight, TBO establishes a trajectory-centric framework for the planning and management of air traffic. While relying less on reactive tactical instructions, operations are guided by a shared 4D trajectory that defines the aircraft's planned lateral path, vertical profile, and timing information. This trajectory is used consistently by both airspace users and service providers to align planning, execution, and monitoring activities.

The value of TBO depends on the degree to which the trajectory used for planning remains consistent with the trajectory that is flown. Air-ground data exchange supports this consistency by making future trajectory information more visible to the ground system and by providing a more structured basis for trajectory updates during operation.

The initial reference trajectory is generated by the aircraft operator based on performance capabilities and operational preferences, and is refined through coordination with the relevant Air Navigation Service Providers (ANSPs) to incorporate route availability, separation requirements, and airspace constraints. Later adjustments may be required due to changing weather, traffic complexity, capacity limitations, or deviations from expected performance before or during flight. Additionally, flight crew preferences or

late-emerging constraints may prompt a revised trajectory, which must be redistributed to all relevant stakeholders.

Maintaining synchronisation between planned and executed trajectories therefore depends not only on initial coordination, but on continuous information exchange throughout the flight. While ADS-C and CPDLC enable tactical updates and conformance monitoring, broader trajectory sharing and constraint management across the network are supported by ground-ground data exchange frameworks such as System Wide Information Management (SWIM) [14, 15].

4.2.1. Expected Benefits in Dutch Flight Information Region

The implementation of TBO is expected to improve the predictability, efficiency, and safety of air traffic operations within Dutch airspace, particularly in the terminal environment surrounding Schiphol Amsterdam Airport. Through ADS-C, intent-based trajectory information becomes available for planning and coordination, while CPDLC enables the agreed trajectory to be communicated to the flight crew and the FMS in a clear and unambiguous digital form. Together, these capabilities strengthen the link between planning, clearance delivery, and execution, reducing reliance on tactical interventions and supporting a more stable traffic flow. Improved predictability of take-off trajectories enables earlier conflict resolution and smoother integration into the European network, while aircraft-derived data for arrivals facilitates cross-border coordination and continuous descent operations. At the network level, consistent use of trajectory information enables Luchtverkeersleiding Nederland (LVNL) to improve demand-capacity balancing and support more energy efficient operations [14].

4.3. Existing TBO Research

Various initiatives have explored the development and implementation of TBO, focusing on operational feasibility, system integration, and performance outcomes. While no framework to date incorporates all components necessary for mixed-equipage TBO, several programmes have addressed foundational elements such as intent sharing, trajectory synchronisation, and decision support.

In Europe, the SESAR programme has conducted extensive research into the technologies and procedures underpinning trajectory-centric operations. While a complete framework accommodating mixed equipage has not yet been developed, SESAR has examined the integration of data link services, automated revision of the Reference Business Trajectory (RBT), and network-wide trajectory sharing through a common prediction service. Its trajectory management framework further addresses cross-border coordination, predictability, and system interoperability, including the use of aircraft-derived data such as ADS-C EPP and the extended flight plan to support CD&R. Together, these initiatives provide the foundation for large-scale TBO implementation, although integration across varying equipage levels remains an open research challenge [16].

Complementary work has been conducted by NASA through its Advanced 4D TBO prototype, which assessed gate-to-gate operations under mixed-equipage conditions. The platform integrated ground-based automation with airborne capabilities via CPDLC and ADS-C EPP, enabling digital trajectory exchange. Evaluations with operational controllers and flight crew demonstrated improvements in predictability and task flow, validating the feasibility of data-driven coordination in realistic en-route scenarios [17]. However, the study did not explicitly incorporate trajectory uncertainty or assess system performance under stochastic variability, which are key elements addressed in the present work.

More directly addressing transition conditions, Gong et al. [18] evaluated a near-term data-link-enabled TBO concept in a mixed-equipage, pilot- and controller-in-the-loop simulation at NASA Ames. The study combined trajectory-based automation at controller positions with CPDLC route and altitude clearances for equipped aircraft, while unequipped aircraft remained voice-based. The evaluated functions included strategic conflict-resolution advisories, tactical conflict detection, and trajectory-based weather rerouting, with scenarios based on Fort Worth Center high-altitude sectors and a 50% fleet-wide data-link equipage assumption. The results indicated that mixed-equipage TBO functions can support controller decision-making, but also highlighted limitations related to data-link response uncertainty, operational acceptability of automated advisories, and trajectory prediction errors during climb. The study therefore provides an important operational demonstration of mixed data-link TBO, although it did not analyse ADS-C EPP-based intent availability.

To support future TBO simulation studies, Buck et al. [19] developed an end-to-end process for generating representative 2040 TBO scenarios in NASA Langley's simulation environment. The scenarios used real-world SWIM traffic data, high-density traffic levels, 4D wind and environmental constraints, ADS-C EPP-based intent exchange, CPDLC trajectory modifications, and a mix of advanced-service and baseline-equipped aircraft. The work focused primarily on scenario construction and simulation-environment realism, including the distinction between free-route aircraft with airborne trajectory-management capability and fixed-route aircraft following recorded baseline trajectories. It therefore provides a relevant basis for modelling future mixed-service TBO environments.

At the national level, the Speed and Route Advisor (SARA) developed by LVNL exemplifies a tactical decision-support tool designed to optimise sector throughput and arrival sequencing through speed and route advisories. Operating solely on ground-based predictions, SARA reduces manual coordination effort by providing conflict-avoidance guidance based on traffic flow forecasts. However, the absence of airborne intent data such as ADS-C EPP, together with limited availability of precise CPDLC capabilities for conveying unambiguous trajectory clearances to the flight deck, constrains the level of trajectory synchronisation achievable in practice [2].

In a more recent study, Scheffers [20] evaluated the impact of enhanced trajectory predictability using ATS data link and ADS-C EPP in lower airspace through fast-time simulations centred on Schiphol. Assuming full equipage, the study examined the effects of varying traffic density, vertical separation buffers, and uncertainty levels. The findings suggest that reduced buffer requirements could improve operational efficiency, although mixed-equipage scenarios and probabilistic conflict modelling were not considered and remain subjects for further research.

4.4. Knowledge Gap

The reviewed studies illustrate significant progress towards TBO, with various initiatives demonstrating how intent data and digital communication can enhance planning, coordination, and predictability. However, these benefits are typically evaluated under full equipage assumptions or within simplified prototype environments. No study was found that systematically examines the operational implications of varying data-link capabilities in realistic en route conditions. In particular, differences in ADS-C intent availability and CPDLC clearance functionality have not been evaluated within an operationally representative environment.

Mixed equipage is expected to remain the norm during the transition to TBO, yet its impact on overall system behaviour is poorly understood. Existing research often assumes universal access to intent information or uniform data-link performance. As a result, the effects of partial equipage on conflict occurrence, trajectory predictability, and controller workload within an operational context remain unclear.

Furthermore, although uncertainty is widely recognised as a limiting factor in trajectory management, its interaction with variation in data-link capability has not been examined. No studies were identified that quantify how differences in update frequency, intent richness, or communication latency propagate uncertainty or influence the robustness of CD&R strategies.

This study addresses these gaps by examining how variation in ADS-C equipage levels and CPDLC capability, in combination with trajectory uncertainty, influences predictability and conflict management performance in Amsterdam ACC airspace.

Review of Modelling Approaches

This chapter reviews modelling approaches relevant to the development of a trajectory management framework for TBO. Section 5.1 introduces the main formulations used for trajectory prediction, followed by the definition of trajectory error metrics in Section 5.2. The principal sources of uncertainty and corresponding quantification techniques are discussed in Sections 5.3 and 5.4. Finally, Sections 5.5 and 5.6 review existing approaches to CD&R that incorporate uncertainty in trajectory prediction.

5.1. Trajectory Prediction

The task of a trajectory predictor is to estimate the future state of an aircraft based on its current state and a defined set of input parameters. The resulting predicted trajectory consists of a sequence of 4D points that describe the aircraft's horizontal position, altitude, and corresponding time along its path. To generate such a prediction, the trajectory predictor requires a mathematical model representing the aircraft's motion. Four principal approaches are commonly applied for the trajectory prediction of conventional aircraft, as illustrated in Figure 5.1.

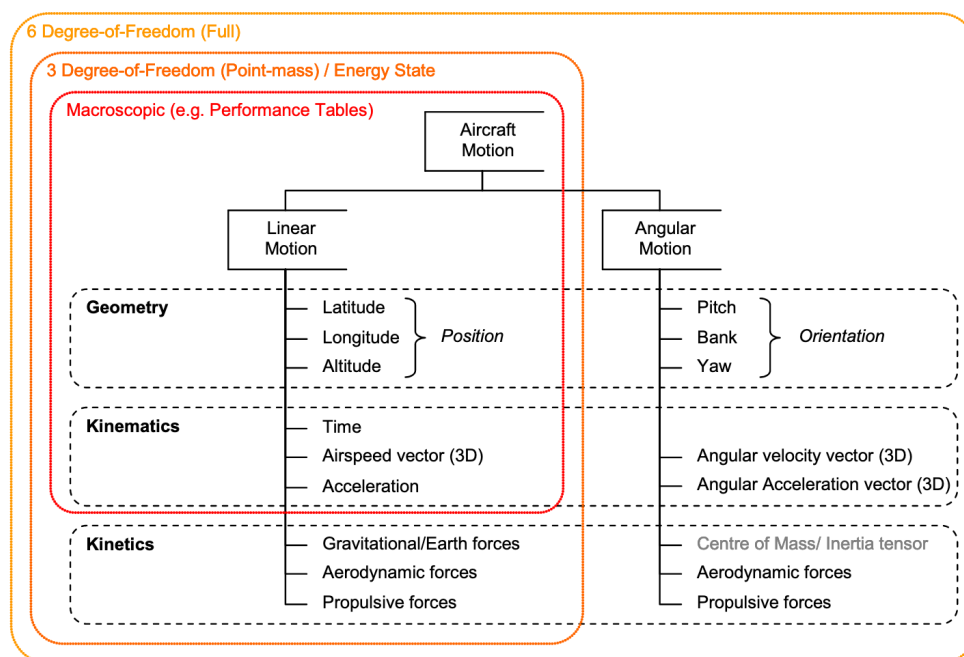


Figure 5.1: Summary of four different mathematical models for trajectory prediction [21].

The highest-fidelity representation is the 6-Degrees of Freedom (DoF) model, which treats the aircraft as a rigid body and resolves three translational and three rotational motions. A lower-fidelity alternative is the 3-DoF point-mass model, which neglects rotational dynamics and assumes all forces act through the

centre of gravity. From this formulation, the total energy model can be derived by expressing the net work done by thrust and drag as a balance between kinetic and potential energy.

At the lowest level of fidelity is the macroscopic or kinematic approach, in which the aircraft motion is not derived from aerodynamic forces or moments but from empirical or statistical relationships. These relationships do not necessarily have a physical basis but describe the aircraft's average performance characteristics. The output variables are typically airspeed and Rate of Climb/Descent (ROCD), provided in static performance tables as a function of altitude [21]. In ATM applications, this macroscopic approach together with the point-mass model are most commonly used.

5.1.1. Trajectory Optimisation

Trajectory optimisation seeks to determine an aircraft path that minimises a specified performance metric while adhering to all relevant physical and operational constraints. This process is governed by a cost function, typically formulated in terms of fuel consumption, flight time, emissions, or a weighted combination of such metrics [22–24]. The selected objective function influences the trade-off between computational efficiency, operational realism, and the environmental or economic priorities embedded within the resulting trajectory.

To ensure dynamically consistent and operationally feasible solutions, constraints are imposed on both the state and control variables. These include boundary conditions that define the initial and final aircraft states, as well as path constraints that limit quantities such as thrust, altitude, vertical speed, and Mach number. Additionally, energy balance relations are introduced to maintain consistency between aerodynamic forces, propulsion input, and the aircraft's available performance envelope [22].

Trajectory optimisation can be formulated in different ways, depending on how the aircraft dynamics and performance objectives are represented. A widely used approach is to formulate the problem as an optimal control problem, in which the aircraft motion is governed by differential equations and the cost function is optimised over a continuous time horizon. Other approaches, including search-based or metaheuristic techniques, rely on discretised representations of the trajectory and often simplify or omit the underlying physical model. The chosen formulation involves a trade-off between physical realism, computational efficiency, and the complexity of the operational setting [23, 24].

Heuristic methods, such as genetic algorithms, simulated annealing, and graph-based strategies like A* search, address the optimisation task through iterative exploration of the solution space rather than through continuous gradient-based optimisation. These methods generally operate on simplified or discretised representations of aircraft motion and often neglect the full dynamic model. Although well suited to nonconvex or discontinuous problems, their limited physical fidelity and high computational cost reduce their suitability for time critical or operationally realistic applications [23, 24].

Within the optimal control framework, two main solution methods are commonly used: indirect and direct methods. Indirect methods first derive the necessary conditions for optimality using analytical tools. This leads to a boundary-value problem in the continuous domain that must be solved numerically. Although this approach can provide high accuracy and strong theoretical guarantees, it is sensitive to initial guesses and difficult to apply to problems with multiple phases or complex constraints. As a result, its use in operational ATM applications is limited.

Direct methods follow a discretise-then-optimize approach, in which the continuous optimal control problem is transcribed into a finite-dimensional nonlinear programming problem. This is done by discretising the trajectory into a sequence of decision variables, typically representing the aircraft states and control inputs at fixed nodes along the time horizon. The resulting optimisation problem can then be solved using numerical techniques. Compared to indirect methods, this approach offers greater flexibility in incorporating complex boundary and path constraints, and is more robust to poor initial guesses. As a result, direct methods underpin many modern trajectory optimisation frameworks [22, 24].

A representative example of a direct optimisation framework is provided by Sun [24], who introduced `OpenAP.top`, an open-source tool for gate-to-gate aircraft trajectory optimisation. The model is based on a simplified three-dimensional point-mass formulation, in which the aircraft states include horizontal position, altitude, and mass, and the control inputs comprise Mach number, vertical rate, and heading angle. Aircraft performance parameters are derived from the `OpenAP` database, providing a transparent and publicly accessible alternative to proprietary datasets such as Base of Aircraft Data (BADA) [25].

The optimisation problem is formulated as an optimal control problem and transcribed into a nonlinear programming problem using direct collocation. This approach enables the efficient computation of time, fuel, or cost optimal trajectories across multiple flight segments. Constraints are imposed on both the state and control variables, including bounds on thrust, altitude, vertical speed, and Mach number, as well as boundary conditions at departure and arrival. To ensure dynamic consistency and trajectory smoothness, additional constraints are introduced to suppress abrupt variations in control inputs. This yields physically plausible solutions suitable for integration into operational environments.

5.2. Error Definitions

Track error can be divided into two types of error. These are the spatial and temporal errors. Both of these errors quantify how much the actual flight path deviates from the predicted trajectory. They will be elaborated on in the following two subsections.

5.2.1. Spatial Error

The concept of spatial error is illustrated in Figure 5.2. It represents the deviation between the actual aircraft position F and the reference position S . The horizontal error can be decomposed into an along-track and a cross-track component. The along-track error e_{along} reflects the displacement in the intended direction of flight and is given by the magnitude $|\vec{SM}|$, where M is the orthogonal projection of the actual position onto the planned path. The cross-track error e_{cross} denotes the lateral deviation from the planned trajectory and corresponds to the perpendicular distance from F to the great circle segment from S to the endpoint E . The directions of $\vec{SP}$ and $\vec{EP}$ represent the meridional vectors from each surface point to the North Pole P , and are used to define the spherical geometry underlying the error decomposition.

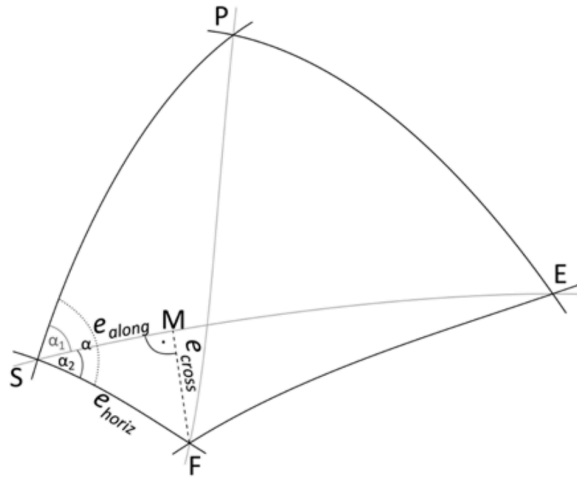


Figure 5.2: Track error divided into along-track and cross-track error [26].

The vertical error is the difference between the actual flight path and the altitude of the predicted trajectory. This is the vector which is orthogonal to the XY-plane. A positive vector indicates that the actual position of the aircraft is above the predicted one. The vertical error, combined with the horizontal error, give the spatial error [26, 27].

5.2.2. Temporal Error

The temporal error can be used to express the time difference between the actual and planned flight position at a certain position along the track. Based on this error, it can be determined if a flight is premature, delayed or on time. Since the temporal error is related to the spatial error, it can be calculated based on the along-track error. Hence, when the along-track error is zero, the aircraft is on time. There can be still be cross-track error in this case [26, 27].

5.3. Sources of Uncertainty

Uncertainty strongly influences how accurately aircraft trajectories can be planned and executed within TBO. Variations in model inputs, environmental conditions, and operational behaviour lead to deviations between predicted and actual aircraft motion, thereby affecting the reliability of trajectory management [26, 28].

The main sources of uncertainty considered are related to the aircraft performance model [29, 30], atmospheric conditions [21, 29–33], flight technical errors [30, 34], the aircraft's initial state [30, 34], and aircraft intent [8, 29, 30, 35, 36]. Each of these factors contributes differently to trajectory prediction uncertainty and is discussed in the following subsections.

5.3.1. Aircraft Model and Performance

To predict the trajectory of an aircraft, a model of its motion is required as described in Section 5.1. The motion is described by a set of equations of motion. In constructing such models, several assumptions and simplifications are made, which contribute to uncertainty in trajectory prediction, as well as the methods to solve those models [29].

Most trajectory prediction models are kinetic in nature. These represent the aircraft by a 3-DoF formulation, in which the effects of angular rates on the predicted trajectory are neglected. This is justified from the ATM perspective, since this information about aircraft attitude does not give significant benefits for efficient ATM. For 3-DoF models, reliable representations of aerodynamic drag, thrust, and fuel consumption under varying flight conditions are needed [30].

A leading initiative in this field is the BADA model, developed and maintained by EUROCONTROL [25]. BADA, and particularly its most recent version 4.0, is regarded as one of the most advanced performance models. The model is based on a kinetic formulation with varying mass which provides the necessary fidelity to represent performance across the flight envelope [25, 28].

Despite its sophistication, uncertainties remain. Discrepancies persist between model outputs and raw performance data. Next to that, is the representation of individual aircraft variability limited by the absence of explicit performance degradation models. Nonetheless, for applications in ATM, models such as BADA are generally considered sufficiently accurate [29].

Additional uncertainty arises from the choice of Earth models and coordinate systems. Approaches differ in their representation of the Earth, ranging from geodetic models to simplified spherical approximations. A commonly used model is the World Geodetic System (WGS) 84, which is considered the one of the most accurate representation available. Errors induced by such models are generally of second order and may therefore be neglected in the context of ATM [29, 30].

5.3.2. Atmospheric Conditions

Aircraft motion is directly affected by the surrounding atmospheric environment. Key parameters include temperature, pressure, air density, and wind. These variables are typically obtained from weather forecasts, which rely on numerical meteorological models and are available only at finite spatial and temporal resolution. As a result, atmospheric inputs inherently introduce uncertainty into the trajectory prediction process [30, 31, 37].

In ATM applications, the International Standard Atmosphere (ISA) is widely adopted as a reference atmosphere. Atmospheric conditions play a critical role in defining airspeed metrics such as True Airspeed (TAS) and Mach number. These quantities are typically computed from calibrated airspeed or Mach number using ambient temperature and pressure data. Above the crossover altitude, Mach number is used to derive TAS, while below this altitude, Calibrated Airspeed (CAS) serves this role. The crossover altitude is defined as the flight level at which both Mach number and CAS yield the same TAS. Errors in atmospheric data, particularly in temperature and pressure, can therefore introduce inaccuracies in these conversions. While the influence of such errors on trajectory prediction is generally regarded as minor compared with wind-related uncertainty [29, 30], they may still contribute to cumulative deviations in long-range computations.

Wind is one of the principal atmospheric factors influencing trajectory prediction accuracy, because trajectory predictors use the forecast wind field to translate aircraft motion relative to the surrounding air mass

into motion relative to the ground [26, 30, 31, 37]. Errors in the headwind or tailwind component modify the along-track component of the ground speed. This causes timing errors and along-track position errors to accumulate over the prediction horizon. Crosswind errors mainly affect the relation between aircraft heading and ground track, and can therefore contribute to lateral deviations. In climb and descent, wind uncertainty can also influence the vertical evolution of the trajectory, since wind gradients with altitude affect the relation between ground speed, path angle, ROCD, and the energy state required to follow the intended vertical profile [30, 38, 39].

For the use of a wind model in trajectory forecasting, wind information across multiple altitude or pressure levels is required. However, operational wind information is not available as a continuous and exact atmospheric field. Instead, it is represented through forecasts with limited spatial resolution, temporal resolution, and vertical discretisation [21, 37]. In the FMS representation discussed by Bronsvort [21], wind profiles are provided at a limited number of discrete altitude levels, as illustrated in Figure 5.3. The FMS then interpolates between these data points to generate a continuous internal wind representation. This interpolation, together with unresolved fine-scale variations and forecast errors, can lead to discrepancies between the actual and internally modelled atmospheric state.

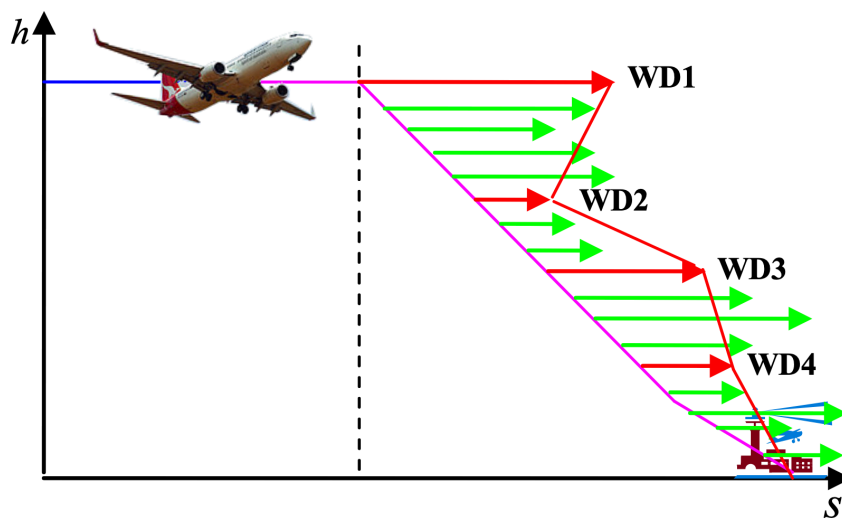


Figure 5.3: Wind forecast model in the FMS [21].

A further source of uncertainty arises when the wind information available to the ground-based trajectory predictor differs from the information used by the flight crew or onboard FMS. In that case, the ground system and the aircraft may propagate the same intended trajectory through different atmospheric representations, resulting in different predictions of position, altitude, and time [9, 21]. In multi-aircraft applications, the spatial correlation of wind forecast errors is also relevant, since aircraft operating in the same region may be affected by related wind errors rather than by independent disturbances [33].

Previous work has shown that the resulting wind-related trajectory prediction uncertainty depends on flight phase, trajectory type, forecast quality, and modelling assumptions. This is particularly relevant for arrival and descent trajectories, where errors in ground speed and vertical-path evolution directly affect the predicted position over time [29, 38]. Recent work on inbound idle and fixed-FPA descents further shows that wind-related uncertainty remains relevant when comparing descent strategies and assessing prediction reliability near the terminal area [39].

In future TBO, more accurate and detailed atmospheric information is expected to support improved air-ground trajectory consistency. More detailed wind profiles and trajectory exchange can allow the onboard and ground-based systems to represent the atmospheric state with higher fidelity. As a result, discrepancies between the actual and modelled wind fields may be reduced, thereby decreasing part of the wind-related uncertainty in trajectory prediction [12].

5.3.3. Flight Technical Errors

Deviations between the intended and actual flight trajectory can arise from imperfections in flight control, commonly referred to as flight technical errors. These deviations occur due to differences in the performance of FMS/autopilot, resulting in minor but persistent inaccuracies [34]. Due to their stochastic nature and independence from specific model parameters or simplifications, such errors are inherently unpredictable and cannot be explicitly modelled [30].

5.3.4. Aircraft Initial State

As discussed previously, the aircraft is modelled using a mathematical system of equations. To initialise this system, the aircraft's initial state must be known. These initial conditions, such as position, velocity, and mass, form the basis for trajectory prediction. Any error in the initial state will propagate through the prediction, thereby reducing its accuracy. Among these parameters, the initial mass is particularly influential [30, 34].

5.3.5. Aircraft Intent

Uncertainty in aircraft intent arises when the sequence of control actions guiding the aircraft's motion is unknown or only partially available to the trajectory predictor. Aircraft intent represents the expected sequence of manoeuvres and target states derived from the flight plan, standard procedures, and Air Traffic Control (ATC) clearances. These manoeuvres are executed by the flight crew or onboard automation and determine how the aircraft responds to its operational objectives and the surrounding environment. Since these actions depend on operational preferences such as airline policy, cost index, and tactical decision-making by the crew, intent uncertainty can originate both from the aircraft's internal performance management and from the way operational intent is communicated between air and ground [8, 29, 30, 35, 36].

The first source of uncertainty relates to performance factors that influence vertical and speed behaviour. Parameters such as thrust setting and cost index play a central role in determining climb rate, cruise speed, and descent initiation, yet these are typically unknown to ground systems. As a result, variability in these parameters propagates directly into altitude and timing predictions. Multiple studies show that climb performance is particularly sensitive to initial mass and vertical speed settings [29, 35, 36]. Descent uncertainty has been linked to variation in thrust and speed profiles [29], the execution of rate-of-descent and level-off instructions [30], and uncertainty in the location of the top of descent [36].

A second source of uncertainty arises from the way intent is communicated and executed through ATC clearances. These may be issued by voice or transmitted digitally via CPDLC, depending on equipment and operational context. Digital transmission may rely on either FANS, ATN B1 or ATS B2 standards, each associated with different message formats and exchange times. The latter enables shorter transaction times and more structured message sets, which supports improved integration with trajectory management. Nevertheless, many clearances lack the precision required for direct use in trajectory prediction.

Ambiguity occurs when key elements, such as the controlled variable, target value, or termination logic, are omitted or insufficiently defined. Instructions expressed as “at or above” or headings without a defined termination point may result in multiple valid interpretations. One such example is shown in Figure 5.4, which illustrates the range of climb trajectories that can follow from a single clearance.

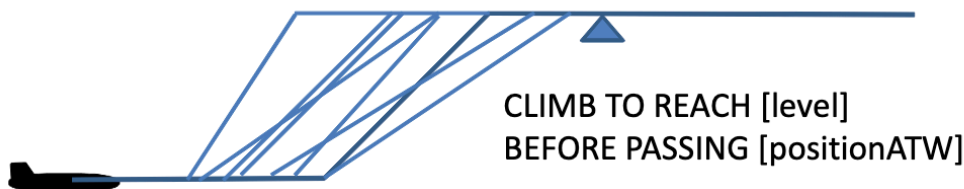


Figure 5.4: Different climb options possible after a climb clearance [8].

This ambiguity also influences the execution phase. Differences in automation logic, pilot response time, and the absence of clearly defined transition profiles, such as vertical speed or acceleration instructions,

contribute to additional variability between the intended and actual trajectory [8, 36]. An analysis of operational message sets found that approximately 52 % of clearances result in more than one feasible trajectory [8]. These findings highlight the need for clearances to be expressed in a structured, machine-readable format that explicitly defines the control objective, magnitude, and condition for execution.

5.4. Quantifying Trajectory Uncertainty

Having identified the primary sources of uncertainty, the following section discusses methods for quantifying and propagating these uncertainties within trajectory prediction models. Knorr et al. [40] represents the spatial uncertainty at a given time as an ellipsoid. The shape and size of this ellipsoid are determined by the spatial accuracy in three orthogonal directions: cross track, along track, and vertical. This concept is illustrated in Figure 5.5. The ellipsoid describes a region within which the aircraft is expected to be located with a given confidence level. Techniques for estimating this uncertainty region are discussed in the following subsections.

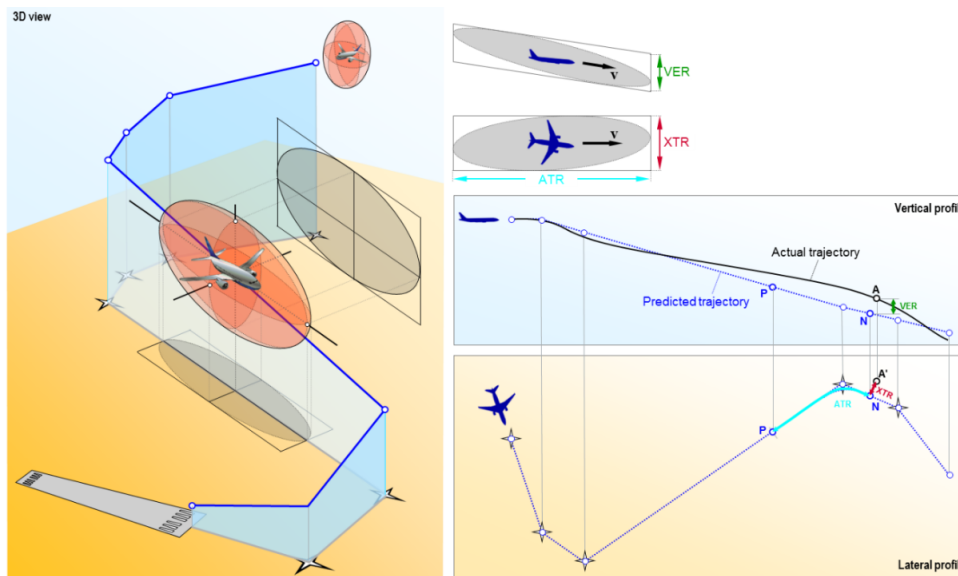


Figure 5.5: Visualisation of spatial trajectory prediction uncertainty [30].

5.4.1. Monte Carlo Simulations

A widely used approach for evaluating uncertainty in trajectory prediction involves the use of Monte Carlo simulations [41]. Each source of uncertainty is described by a probability distribution, often Gaussian with parameters based on measurement data [29, 42]. Yet, Rudnyk et al. [35] showed that many input errors, especially in kinematic models, do not follow simple Gaussian or uniform distributions.

By repeatedly sampling from these distributions, a large set of possible trajectories is generated. The result is a cloud around the nominal prediction, from which measures such as variance, confidence intervals, or probability contours can be derived. This approach allows for combining multiple sources of uncertainty without assuming linearity, though it requires significant computational effort to obtain statistically robust outcomes.

5.4.2. Polynomial Chaos Expansions

As a more computationally efficient alternative to Monte Carlo methods, Polynomial Chaos Expansions (PCE) enables the propagation of uncertainty with significantly fewer simulations. The method represents a random variable as a polynomial function of other random variables, where the multivariate polynomials form an orthogonal basis for the input parameters. In this way, uncertainty in the inputs is directly translated into trajectory uncertainty. Although the number of equations increases with the input dimension and the polynomial order, the approach remains substantially less demanding than running thousands of Monte Carlo simulations. Due to its ability to approximate complex input–output relationships using a compact

functional representation, PCE is particularly well suited for studying nonlinear effects in high-dimensional systems. However, its applicability may be limited in problems with discontinuous response surfaces or a large number of uncertain parameters, where the required polynomial order becomes prohibitively high [30, 43, 44].

5.4.3. Bayesian Entropy

Uncertainty estimates can be refined through a process of Bayesian updating, in which prior knowledge is combined with observed data using a likelihood function to produce a posterior distribution [45]. The Bayesian-Entropy method extends this approach by incorporating the Maximum Entropy principle, enabling the simultaneous use of simulation data, physical constraints, and expert knowledge. In trajectory prediction, this method has been applied to fuse model-based forecasts with real-time traffic data to calibrate uncertainty more accurately. Its strength lies in the systematic integration of multiple data sources, allowing prior estimates to be updated based on observed spatial deviations. However, the method relies on Monte Carlo simulations to compute posterior distributions, which limits its applicability in real-time settings. Moreover, it focuses on uncertainty along fixed routes rather than dynamically generated trajectories, making it less suitable for applications involving individual aircraft intent or high-temporal-resolution updates.

5.5. Conflict Detection

Within ATM, the assurance of safety is of critical importance. To this end, minimum separation standards are defined in both the horizontal and vertical dimensions, and a potential conflict arises when two aircraft are predicted to violate these minima. Anticipating such situations requires a conflict detection mechanism, which forms the first stage of CD&R. Once a conflict is detected, resolution strategies can be applied to ensure safe separation.

Conflict detection can be approached in several ways. Deterministic methods assess whether predicted nominal trajectories will infringe separation standards, while probabilistic methods extend this by explicitly modelling the uncertainty around those trajectories. The latter have received significant attention, as they provide a framework to quantify conflict likelihood rather than merely indicating its possibility. Depending on the operational context, these methods can be applied over different look-ahead horizons.

5.5.1. Conflict Detection Horizons

Conflict detection is commonly categorised into three levels according to the prediction horizon. The first is the long range, corresponding to horizons of several hours and typically applied during the flight planning stage on a system-wide basis. The second is the mid-range, where conflicts are predicted on horizons of 8 to 20 minutes, and which is most relevant for en-route operations. The third is the short range, where conflicts are identified on horizons of seconds to minutes. This short-range detection can also be carried out onboard by the aircraft's FMS [46]. In the context of TBO, as considered in this research, emphasis is placed on mid-range conflict detection during the en-route phase.

5.5.2. Probabilistic Methods

Probabilistic methods estimate the likelihood of conflict by explicitly modelling uncertainty in aircraft trajectories. In this work, two principal families are distinguished. The first comprises analytical probability models, which compute conflict likelihood using simplified statistical assumptions and closed-form expressions. The second includes geometric reach-set models, which represent uncertainty through sampled trajectory ensembles and assess conflict by evaluating the intersection of reachable sets.

Analytical Probability Models

The concept of probabilistic conflict detection is illustrated in Figure 5.6, which considers two aircraft: the reference aircraft R and a second aircraft S . At a given prediction time t , both aircraft have known nominal positions, but only aircraft S is subject to prediction uncertainty. This uncertainty is represented as an ellipsoid centred on the predicted position of S , as introduced in Section 5.4. Around the position of aircraft R , a cylindrical protection zone is defined, corresponding to the minimum separation standards. This zone typically has a horizontal radius of 5 NM and a vertical extent of 1000 ft.

Following the method of Paielli et al. [47], and its three-dimensional extension by Li et al. [48], the probability of conflict is defined as the probability that the error ellipsoid of aircraft S intersects the protection

zone of aircraft R at time t .

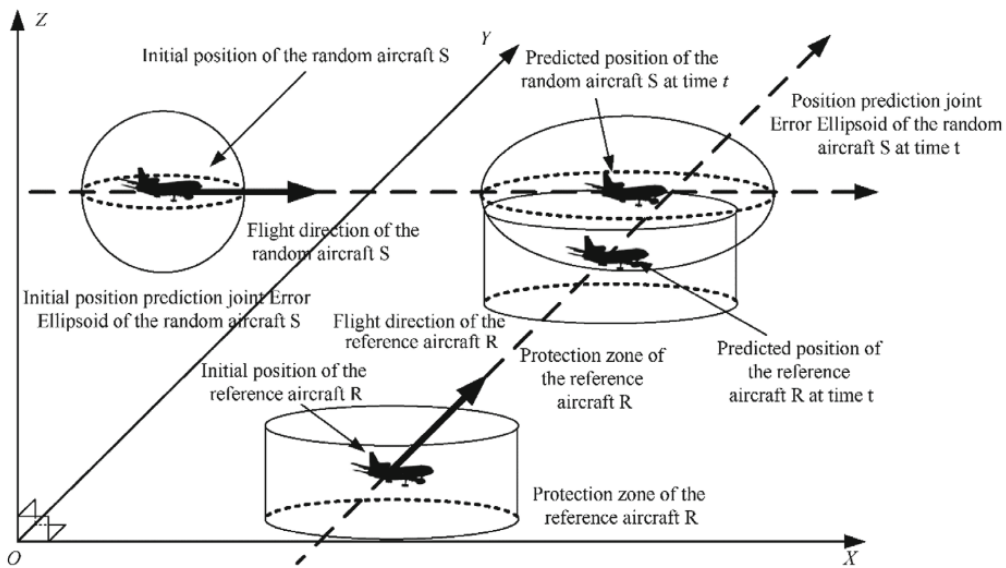


Figure 5.6: Schematic illustration of the conflict detection concept [48]

The probabilistic approach proposed by Paielli et al. [47] provides a framework for estimating the likelihood of conflicts. However, it is limited to pairwise encounters. In practice, conflict resolution requires a multi-aircraft optimisation, since resolving a conflict between two aircraft may inadvertently create new conflicts with others [46].

Li et al. [48] extend the probabilistic conflict detection method of Paielli et al. [47] from two to three dimensions. In this approach, the time-dependent positional uncertainty of an aircraft is superimposed on its planned trajectory, resulting in a probabilistic representation of its future position. Based on this probabilistic trajectory, the conflict probability with another aircraft can be computed with respect to the prescribed separation standards.

During flight, the predicted and actual aircraft positions can be compared to define the position prediction error $\tilde{q}(t)$, which quantifies how the estimated trajectory deviates from the realised one. The positional uncertainty is described by its standard deviations σ_x , σ_y , and σ_z , corresponding respectively to the longitudinal (along-track), lateral (cross-track), and vertical components of motion. These components are defined within a local coordinate system aligned with the aircraft trajectory, allowing uncertainty growth to be modelled consistently along and perpendicular to the flight path.

Earlier probabilistic models, such as that of Prandini et al. [46], assumed that the along-track and cross-track variances increase quadratically with look-ahead time or distance. This reflects the general principle that uncertainty grows as the prediction horizon extends. However, these assumptions tend to overestimate positional uncertainty for modern FMSs, which continuously correct deviations through closed-loop guidance.

Li et al. [48] refined this modelling approach by reformulating the error distribution in a local trajectory-aligned coordinate system and extending it to three spatial dimensions. Although the model still depends on the look-ahead time, it provides a more realistic spatial characterisation of uncertainty around the predicted trajectory. In their approach, the longitudinal and vertical uncertainties grow approximately linearly with time, while the lateral uncertainty remains nearly constant due to the tight control of lateral path tracking provided by the FMS. The longitudinal growth rate depends on whether the aircraft operates under three- or 4D trajectory guidance, whereas the vertical component includes a constant offset representing the barometric altimeter error. This formulation generalises the earlier two-dimensional models while more accurately capturing the navigational performance of present-day aircraft.

The predicted aircraft position at time t is modelled as a Gaussian distribution centred on the nominal

trajectory, with covariance matrix

$$S_{\Theta_1}(t) = \text{cov}(\tilde{q}_{\Theta_1}(t)) = \begin{bmatrix} \sigma_x^2(t) & 0 & 0 \\ 0 & \sigma_y^2(t) & 0 \\ 0 & 0 & \sigma_z^2(t) \end{bmatrix}, \quad (5.1)$$

where the diagonal elements represent the variances along the longitudinal, lateral, and vertical axes of the local trajectory-aligned frame Θ_1 .

For multi-aircraft analysis, each aircraft's local covariance matrix can be rotated into a common ground-based reference frame using its course angle. This enables conflict detection to be performed in a unified spatial context. The relative position between two aircraft is defined as the difference between their predicted positions in this common frame. Under the assumption of uncorrelated and independent errors, this relative position follows a normal distribution with a mean equal to the nominal position difference and a covariance given by the sum of the individual covariances. Although this simplification neglects spatial correlations such as shared wind errors, it provides a conservative approximation that may slightly overestimate the probability of conflict [33].

Finally, the instantaneous probability of conflict is defined as the probability that this relative position lies within the cylindrical protection zone of radius s_c and vertical half-height $h/2$:

$$PC(t) = \iiint_{V_{PZ}} p(x, y, z) dx dy dz, \quad (5.2)$$

where $p(x, y, z)$ denotes the joint probability density of the relative position.

Direct evaluation of Equation (5.2) is analytically intractable. Li et al. [48] therefore reformulate the problem using linear transformations, leading to a closed-form solution that expresses $PC(t)$ as a product of standard normal cumulative distribution functions in the longitudinal, lateral, and vertical directions. This avoids numerical integration and makes the method suitable for real-time applications.

The algorithm then defines a measure of criticality as the maximum instantaneous conflict probability within the prediction horizon:

$$C = \max_{t \in [0, T_{\text{tot}}]} PC(t). \quad (5.3)$$

This measure captures the highest risk of conflict and provides the decision criterion for whether a predicted encounter should trigger a resolution manoeuvre [46].

Reach Set Models

Another probabilistic approach is discussed by Yang et al. [49]. In this study, no Gaussian assumption of the tracking error is imposed. Instead, probabilistic reach sets are introduced to characterise stochastic uncertainty over a mid-term horizon of approximately 15–20 minutes. These reach sets are obtained by formulating a chance-constrained optimisation problem, solved using the scenario approach, which requires many trajectory simulations in an air traffic simulator.

Conflict detection is defined as the intersection of the resulting probabilistic reach sets. At each time step, ellipsoidal sets are fitted to the simulated trajectories, representing the region of the airspace that an aircraft occupies with probability at least $1 - \varepsilon$, where ε is a user-defined risk threshold specifying the maximum allowable probability of the aircraft being outside the set. A conflict is detected when the ellipsoids of two aircraft overlap within the look-ahead horizon. This shifts the detection task from closed-form probability evaluation, as in Gaussian-based methods, to a geometric characterisation of uncertainty that remains valid under more general disturbance models.

5.5.3. Intent-Based Methods

An alternative approach is proposed by Hao et al. [50], in which uncertainty in aircraft intent is addressed through the concept of a Space–Time Prism (STP), drawing on the framework of time geography. In this formulation, an aircraft's 4D trajectory is represented as a sequence of route segments between waypoints, each constrained by a Constrained Time of Arrival (CToA). The conventional CD&R process of trajectory prediction, conflict detection, and resolution is reformulated into three steps: calculation of potential path

spaces, identification of the Space–Time Potential Conflict Space (STPCS), and conflict-free trajectory planning.

Conflict detection is performed by constructing a STP for each aircraft. The STP defines the set of positions that can be reached within spatial and temporal bounds, given the aircraft's maximum velocity and waypoint CToAs. The intersection of two or more STPs defines the STPCS, which represent the regions in space and time where a conflict may occur. This approach does not rely on a single nominal trajectory with added uncertainty bounds. Instead, it characterises the full set of feasible trajectories implied by intent and timing constraints. Intent is represented by the planned waypoint sequence, and the timing constraints defined by the required CToAs. In this way, the method shifts the focus from stochastic execution uncertainty to the structured uncertainty arising from flexibility in fulfilling intent.

This intent-based approach complements the reach-set framework of Yang et al. [49], which focuses primarily on uncertainties in execution. Hao's method broadens probabilistic modelling by incorporating intent uncertainty, which is particularly relevant in TBO where flexible adherence to time constraints is expected. A limitation of the method is the assumption that CToAs are known for all waypoints, which may not hold in mixed-equipage TBO environments, where time constraints are typically applied only at selected metering points.

5.6. Conflict Resolution

Conflict resolution has been studied through a variety of modelling paradigms that differ in their degree of automation, treatment of uncertainty, and operational integration. Among these, the two-leg manoeuvre is one of the most widely adopted structures, representing the aircraft trajectory as two connected segments defined by an intermediate waypoint between the current position and the destination. This structure is frequently adopted in optimisation-based methods [32, 51–54], controller-in-the-loop methods [55, 56], and strategic pattern-based planning [57]. These will all be discussed in the following subsections.

5.6.1. Optimisation-Based Methods

Optimisation-based conflict resolution treats the deconfliction problem as a mathematical programme in which aircraft trajectories are parameterised and adjusted to minimise a defined cost while satisfying separation constraints. These approaches offer a framework for safety and performance but differ in how they represent dynamics and uncertainty. Two main groups can be identified: deterministic formulations, which assume perfectly known system states, and stochastic formulations, which explicitly account for trajectory uncertainty.

Deterministic Formulations

Hu et al. [51] propose a deterministic conflict-resolution method based on two-leg trajectory optimisation. Each trajectory includes one intermediate waypoint between the aircraft's current position and destination, allowing conflict-free paths to be generated geometrically around a cylindrical protection zone. In multi-aircraft scenarios, the intermediate waypoints act as decision variables in a joint optimisation problem.

Aircraft are modelled kinematically as point masses flying at constant speed, with instantaneous heading and altitude changes permitted at waypoints. The objective minimises total path length, expressed as

$$J(\alpha_i) = \frac{1}{2} \int_{t_0}^{t_f} \left[\|\dot{\alpha}_{i,xy}(t)\|^2 + \eta^2 |\dot{\alpha}_{i,z}(t)|^2 \right] dt \quad (5.4)$$

where the total cost is defined by the manoeuvre α_i , combining lateral and vertical components. A vertical penalty term $\eta \geq 1$ is applied to discourage altitude changes unless lateral deviations are insufficient.

By including operational constraints on turn angle and speed, the optimisation problem becomes a Second–Order Cone Programming (SOCP). In a representative case with eight aircraft, conflict-free trajectories were obtained within 26 s, demonstrating computational efficiency suitable for near-real-time application. Despite relying on simplified kinematics and neglecting uncertainty, the method offers a structured framework for cooperative conflict resolution and has since become a widely cited reference in the CD&R literature.

Building on the work of Hu et al. [51], Raghunathan et al. [52] extend the deterministic framework by introducing a full point-mass aircraft model to ensure that the generated trajectories are physically flyable.

Whereas Hu's formulation assumes constant speed and instantaneous heading changes, this approach introduces continuous control over thrust, bank angle, and flight-path angle, thereby enforcing realistic flight dynamics. The protection zone remains modelled as a fixed cylinder, and air density is assumed constant to simplify the equations of motion. The method targets planning horizons of approximately 15 min to 20 min.

Although computationally more demanding than Hu's model, the method remains tractable: four-aircraft scenarios resolve in about 8 s, and eight-aircraft cases in roughly 651 s. This extension enhances the physical realism and fly-ability of the trajectories while maintaining computational feasibility, though convergence remains sensitive to discretisation, initialisation, and solver tuning.

Optimisation under Uncertainty

In contrast to deterministic optimisation, several studies incorporate uncertainty directly into the conflict resolution process. Yang et al. [53] extend the two-leg manoeuvre framework of Hu et al. [51] by applying the probabilistic reachability concept previously discussed for conflict detection (see Subsection 5.5.2). In this method, the intermediate waypoint of each trajectory is optimised while conflict likelihood is evaluated at discrete time steps through the intersection of ellipsoidal reach sets. The objective function combines two terms: the control energy of the nominal trajectory and the cumulative probability of conflict along the prediction horizon. This formulation explicitly captures execution uncertainty, offering a stochastic alternative to Hu's deterministic model. However, the computational cost of reach-set generation remains significant, with total runtimes exceeding 22 000 s in dense multi-aircraft scenarios, limiting its operational feasibility.

Lecchini Visintini et al. [54] pursue a similar objective by jointly minimising deviation cost and conflict probability, but within a Monte Carlo optimisation framework. Candidate manoeuvres are parameterised and evaluated under stochastic trajectory realisations, with a Markov Chain Monte Carlo procedure used to explore the manoeuvre space. Acceptance or rejection of each candidate depends on its expected conflict probability and deviation cost. While this method flexibly accommodates multi-aircraft encounters and nonlinear uncertainties, computation times of several hours restrict its operational feasibility for strategic conflict management.

A more operationally focused extension is presented by Hernández-Romero et al. [32], who introduce a probabilistic CD&R model that incorporates wind forecast uncertainty. Aircraft trajectories are parameterised by displacing selected waypoints, and the optimisation minimises deviation from the nominal flight plan. This can be measured by the Euclidean distance between modified and reference paths. Hence airline route preferences can be maintained. Conflict probability is iteratively reduced in two stages: an initial deterministic resolution using the mean wind field, followed by a probabilistic refinement enforcing a maximum conflict-probability threshold. The framework demonstrates reduced conflict likelihood under realistic wind conditions, but its scope remains limited to cruise operations, excluding climb and descent phases.

5.6.2. Controller-in-the-Loop and Solution-Space Methods

While Hu et al. [51] and Raghunathan et al. [52] formulate conflict resolution as an optimisation problem, later studies have explored controller-oriented approaches that retain the two-leg manoeuvre structure but simplify computation. Klomp [55] proposes such a concept, focusing on the development of an interface to support conflict resolution decisions. When two aircraft are in potential conflict, a solution space is constructed by varying the position of an intermediate waypoint laterally around the nominal route. Each variation defines a two-leg trajectory connecting the current aircraft position to a fixed end waypoint at the RTA. For every candidate waypoint, the necessary speed adjustment is computed to ensure compliance with the fixed RTA.

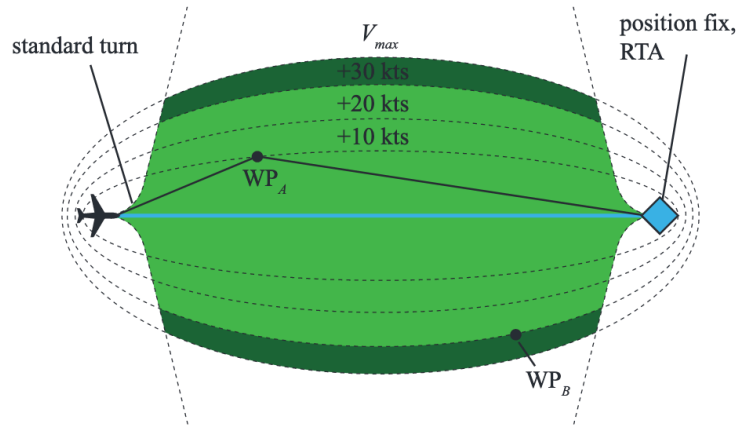


Figure 5.7: Lateral rerouting possibilities with RTA [56].

The solution space is generated through a grid search in which the intermediate waypoint is displaced laterally within a predefined area, as illustrated in Figure 5.7. For each grid point, the required speed change is calculated and retained if it remains within permissible limits. The valid points collectively form the feasible solution space, which is then visualised for controller selection. This method considers only lateral deviations and neglects vertical manoeuvres.

Ottenhoff [56] extends this framework by including both lateral and vertical deviations, as well as wind effects and trajectory uncertainty. For each potential waypoint location, the required speed change is computed and combined with a conflict-probability assessment following Paielli et al. [47]. Points are accepted only if the speed change is feasible and the conflict probability remains below a defined threshold. Lateral rerouting is limited by operational speed boundaries, while vertical manoeuvres are constrained by altitude regulations and the aircraft's performance envelope. As in the previous study, the resulting solution space is presented to the controller for selection, and the analysis is restricted to two-aircraft scenarios.

5.6.3. Strategic and Pattern-Based Planning Methods

Beyond optimisation-based techniques, other studies explore strategic conflict prevention through trajectory pattern design. Valenzuela et al. [57] propose a method for managing inbound traffic converging to a common IAF. The framework employs a set of pre-defined trajectory patterns that represent typical arrival flows and operational constraints. By selecting and adjusting these patterns, the method constructs conflict-free approach paths up to the IAF, ensuring stable sequencing before terminal entry.

This pattern-based approach operates in the pre-tactical phase, assuming that trajectories can be modified freely before entering the controlled terminal area. Its advantage lies in its simplicity and suitability for structured arrival management under high traffic density. However, the concept applies exclusively to inbound operations and does not extend to en-route or outbound traffic, limiting its generalisability for system-wide conflict resolution.

Research Questions

This chapter defines the research objective and corresponding research questions that guide the study. These were formulated in response to the gaps identified in the preceding chapter, which showed that limited research has examined how variations in data-link capabilities, such as ADS-C and CPDLC, affect the transition towards TBO within the Amsterdam ACC domain. While several studies explore the potential of scenarios with full equipage, little is known about the transitional phase in which aircraft with differing capabilities operate simultaneously under operational constraints. This study addresses that shortfall by examining how equipage variation and trajectory uncertainty influence conflict management, predictability, and overall system performance.

The main objective of this research is presented below. It describes the overall aim of the study and forms the basis for the specific research questions that follow.

Research Objective

The research objective is to evaluate how variations in ADS-C equipage and CPDLC capability influence conflict management, trajectory predictability, and efficiency within Amsterdam ACC airspace by developing and testing a trajectory management framework that integrates trajectory optimisation, uncertainty modelling, and conflict detection and resolution.

To achieve this objective, the following main research question has been formulated. It addresses the central focus of the study and provides the link between the literature findings and the proposed simulation framework.

Research Question

How do variations in ADS-C equipage ratio and CPDLC capability levels among aircraft affect the performance of a trajectory management framework within Amsterdam ACC airspace?

The main research question is further divided into supporting questions that address its key components.

Supporting Questions

- SQ1:** Which Key Performance Indicators (KPIs) are most suitable to assess safety, efficiency, and predictability under mixed data-link equipage conditions?
- SQ2:** How can a trajectory management framework be developed to support the evaluation of mixed-equipage operations?
- SQ3:** How does the integration of ADS-C intent information influence conflict detection and resolution performance in mixed-equipage operations?
- SQ4:** How do variations in ADS-C equipage ratio and CPDLC capability levels affect conflict occurrence, trajectory predictability, and efficiency in representative Amsterdam ACC scenarios?
- SQ5:** Which trajectory-uncertainty parameters most strongly affect conflict probability, efficiency, and model robustness?

Project Plan

With the research questions defined and the background established, this chapter outlines the project plan that will guide the execution of the research. First, the proposed methodology is described in Section 7.1, explaining how the research questions will be addressed and detailing the associated uncertainties, assumptions, and simulation logic. The expected results are subsequently presented in Section 7.2, followed by the overall project planning in Section 7.3.

7.1. Methodology

This study employs a simulation-based framework to assess the impact of mixed ADS-C equipage and trajectory uncertainty on conflict management in Amsterdam ACC. Simulations are conducted using the BlueSky air traffic simulator, which allows for the integration of custom modules and provides an open, scriptable environment suitable for large-scale experimentation.

Representative traffic scenarios are constructed for the ACC domain (FL 095–FL 245), with varying equipage ratios and capabilities. Prior to each simulation run, trajectories are optimised for all aircraft. ADS-C-equipped aircraft follow energy-optimal 4D profiles, while conventional aircraft are restricted to airway-constrained routes optimised in the vertical dimension. These nominal trajectories form the basis for subsequent CD&R.

Uncertainty is introduced through stochastic sampling of key variables. Conflicts predicted before the start of the simulation are resolved in advance. During the simulation, aircraft evolve dynamically under execution uncertainty. The conflict-detection module continuously monitors separation risk, and the resolution module intervenes when predefined thresholds are exceeded.

All conflicts, resolutions, and deviations are recorded for post-processing. Conflicts occurring outside the look-ahead horizon are not resolved but logged as indicators of residual risk. This setup enables systematic evaluation of safety and efficiency across equipage and uncertainty conditions.

7.1.1. System Components

The simulation framework comprises three main components: trajectory optimisation, conflict detection, and conflict resolution. These modules form the core of the trajectory management model and govern how aircraft trajectories are generated, evaluated, and adapted under mixed-equipage conditions.

Trajectory Optimisation

Trajectories are generated using the three-dimensional formulation of Sun [24], implemented via the `OpenAP.top` library. The method yields energy-optimal paths that respect aircraft performance limits while maintaining the computational efficiency required for Monte Carlo analysis. Its open-source structure ensures reproducibility and facilitates integration with the BlueSky simulator.

For ADS-C-equipped aircraft, both lateral and vertical profiles are optimised to minimise fuel usage, enabled by the availability of detailed intent via periodic EPP reports. Conventional aircraft are restricted to predefined airways and optimised only in the vertical domain. The resulting nominal trajectories form the basis for CD&R.

Conflict Detection

The conflict detection module builds on the probabilistic framework of Li et al. [48], extending the analytical model of Paielli et al. [47]. Each trajectory is modelled as a time-varying distribution around its nominal path, with directional covariances capturing dispersion in the along-track, cross-track, and vertical axes. This enables continuous evaluation of conflict probability across the look-ahead horizon. The method balances analytical tractability with computational speed, making it suitable for large-scale stochastic simulation.

Conflict Resolution

Conflict resolution uses two-leg manoeuvres, based on the formulation by Hu et al. [51], introducing an intermediate waypoint before returning to the original path. The manoeuvre minimises path length while satisfying aircraft performance constraints. For inbound flights, adherence to the EAT at the IAF is ensured using the binary search speed-adjustment method from Ottenhoff [56], applied only when necessary to satisfy time constraints.

Resolution outcomes are assessed using the probabilistic conflict model of Li et al. [48], ensuring robustness under uncertainty. If the two-leg approach is infeasible due to for example complex geometries or high traffic density, the framework can be extended with the dynamic optimisation method of Raghunathan et al. [52]. Other resolution techniques are excluded due to their geometric simplifications, neglect of uncertainty, or computational inefficiency.

7.1.2. Uncertainty

Uncertainty is modelled as a combination of intent uncertainty and execution uncertainty. Intent uncertainty refers to incomplete knowledge of the trajectory that the aircraft is expected to follow, including the availability of route, speed, altitude, and vertical-profile information. This component is mainly affected by the aircraft equipage level, since more advanced datalink capabilities can provide a more complete description of the planned trajectory.

Execution uncertainty refers to deviations that occur while the aircraft follows its intended trajectory. These deviations can arise from variability in aircraft performance, speed and vertical-profile tracking, and the atmospheric conditions encountered during flight. Wind is therefore included as part of the execution uncertainty, since differences between the predicted and realised wind field affect the aircraft motion relative to the ground.

In the simulation framework, the uncertainty model is split accordingly. The intent component represents uncertainty in the available trajectory information, while the execution component represents uncertainty in how accurately this trajectory is realised. A Monte Carlo approach is used to propagate these uncertainties through repeated scenario realisations, allowing the resulting impact on CD&R performance to be assessed statistically.

7.1.3. Performance Metrics

Framework performance is evaluated in terms of conflict-management performance and operational efficiency. Conflict-management performance is assessed using the number of conflicts and the number of accepted trajectory adjustments. The number of conflicts indicates the residual separation performance of the framework, while the number of trajectory adjustments reflects the intervention demand imposed on the traffic sample.

Operational efficiency is assessed using flown track miles and modelled work. Flown track miles quantify the lateral efficiency of the resulting trajectories, while modelled work provides an indication of the additional operational cost associated with trajectory changes. Together, these metrics allow the effect of traffic demand and equipage composition to be compared across the tested simulation conditions.

7.1.4. Assumptions

The implementation of the proposed framework requires several simplifying assumptions to ensure computational feasibility while maintaining the essential operational characteristics of the Amsterdam ACC environment. These assumptions define the boundary conditions of the simulation and clarify the scope within which the results should be interpreted.

Table 7.1: Overview of independent and dependent variables in the simulation experiment

Independent variables	Dependent variables
Traffic scenario	Flown track miles
Equipage composition	Number of conflicts
	Modelled work
	Number of trajectory adjustments

- Modelling errors arising from aircraft performance models, spherical-Earth approximation, and numerical simplifications are neglected, as their effect on trajectory prediction accuracy is considered minor compared with other uncertainties.
- All aircraft follow nominal operations, with no weather deviations, equipment failures, or emergency procedures.
- Aircraft are represented as point-mass models.
- The CD&R process is centralised and assumed to have instantaneous access to all aircraft states and intents.
- ADS-C-equipped aircraft are assumed to downlink valid intent information continuously and without communication delay or loss.
- The simulation horizon represents a medium-term planning timescale of approximately 8–20 minutes.
- Inbound aircraft are delivered to the IAF at 10 000 ft with a fixed EAT.
- The top-of-descent point is treated as an independent variable but remains outside the influence of the ATM system, as it lies beyond the boundaries of the modelled FIR.

7.2. Expected Results

Increasing the ADS-C equipage ratio is expected to reduce the number of conflicts beyond the CD&R look-ahead horizon, with the largest improvements occurring between low and moderate equipage levels. Beyond this range, a saturation effect is anticipated, where further equipage yields limited benefit. At very high equipage levels, total track miles and energy consumption may rise slightly due to increased trajectory coordination and secondary deconflictions.

CD&R is expected to be most challenging in the vicinity of the IAF, where inbound flows must be merged and sequenced within limited airspace. In these regions, the advantages of intent sharing are likely to be most pronounced. Among the uncertainty parameters considered, initial aircraft mass is expected to have the greatest influence on both conflict probability and overall efficiency.

7.3. Planning

To ensure effective research execution, the project is structured into nine distinct work packages (WPs), each targeting specific milestones and deliverables. The WPs are designed to build upon each other, culminating in a comprehensive simulation framework capable of evaluating TBO under mixed equipage and uncertainty conditions. The work packages are illustrated in Figure 7.1.

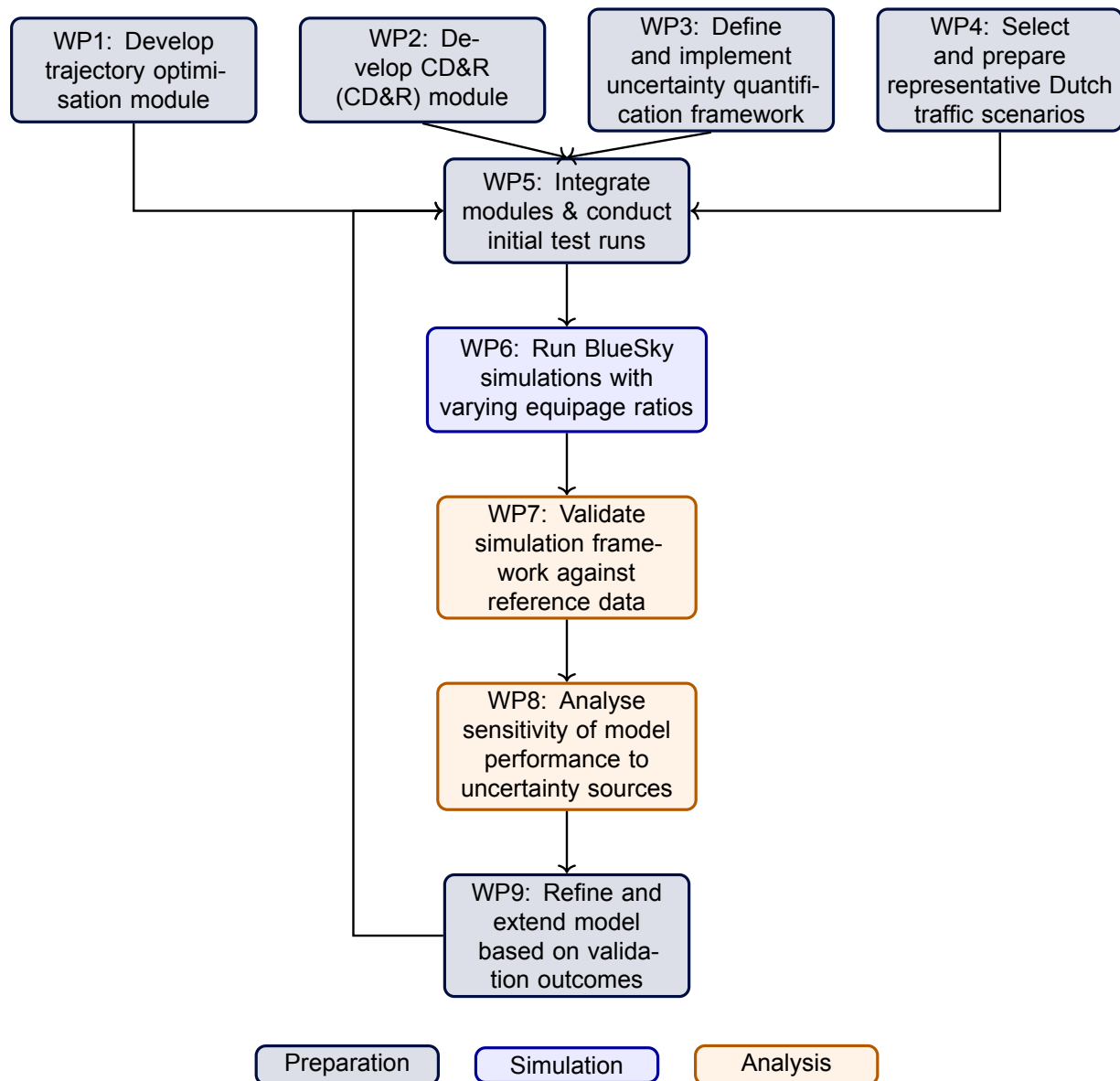


Figure 7.1: Work packages of the research project divided into preparation, simulation and analysis phases with a loop to increase model complexity based on validation results.

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