



Analysis and prediction of pilot response time to air traffic control clearances

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Abstract

With increasing automation of Air Traffic Management, new digital systems need to adapt to uncertainties caused by human behavior. One such uncertainty is the pilot response time after an air traffic control clearance issued by the Air Traffic Controller (ATCO). This study investigates factors influencing pilot response times using the Swedish Civil Air Traffic Control (SCAT) dataset by analysing roughly 830,000 clearances collected over 13 weeks. We find that pilot reactions vary significantly depending on altitude, time of day, and the maneuver delta requested by the ATCO. Lower altitudes (0–100 FL) exhibit shorter maneuver initiation delays compared to higher altitudes (300+ FL). The maneuver completion time for heading and level changes strongly correlates with the magnitude of change, whereas this correlation is weaker for speed adjustments. Although slight variations exist between airlines and aircraft types, these factors have less influence on the pilot response time. Based on these findings, we investigate the predictability of both initiation delay and maneuver completion delay. This is done by training and evaluating the performance of a machine learning model. Our model shows that maneuver completion times are highly predictable ($R^2 > 0.73$) across all clearance types, while initiation delays prove more challenging to forecast accurately.

Keywords Pilot response time · Air traffic control clearance · Air traffic management · Maneuver complexity · Machine learning

1 Introduction

Artificial Intelligence (AI) is rapidly transforming many fields, including Air Traffic Control (ATC). Many recent advances in digital ATC assistance systems are based on AI, and this trend is expected to continue [1]. AI-based systems, such as the Digital Interactive Reliable Controller (DIRC) developed by DLR [2, 3], aim to support or collaborate with

human controllers by autonomously issuing clearances in certain scenarios. These systems operate at the critical interface between Air Traffic Controllers (ATCOs) and pilots. While pilots often rely on automation systems like the autopilot, maneuvers explicitly instructed by ATC still necessitate human interaction including receiving, understanding, acknowledging, and initiating the clearance via communication channels.

This essential human involvement introduces variability and uncertainty into how and when clearances are executed. Figure 1 provides an illustration: multiple aircraft receiving the exact same clearance exhibit widely divergent trajectories. The final position after completing the maneuver can differ by nautical miles, primarily due to variations in the pilot's behavior before and during the execution of the maneuver which are influenced by the dynamic conditions faced by each flight. Human ATCOs develop expertise in anticipating and managing this variability. However, for digital ATC systems, this uncertainty presents a major challenge. These systems rely on accurate trajectory predictions to optimize traffic flow, ensure

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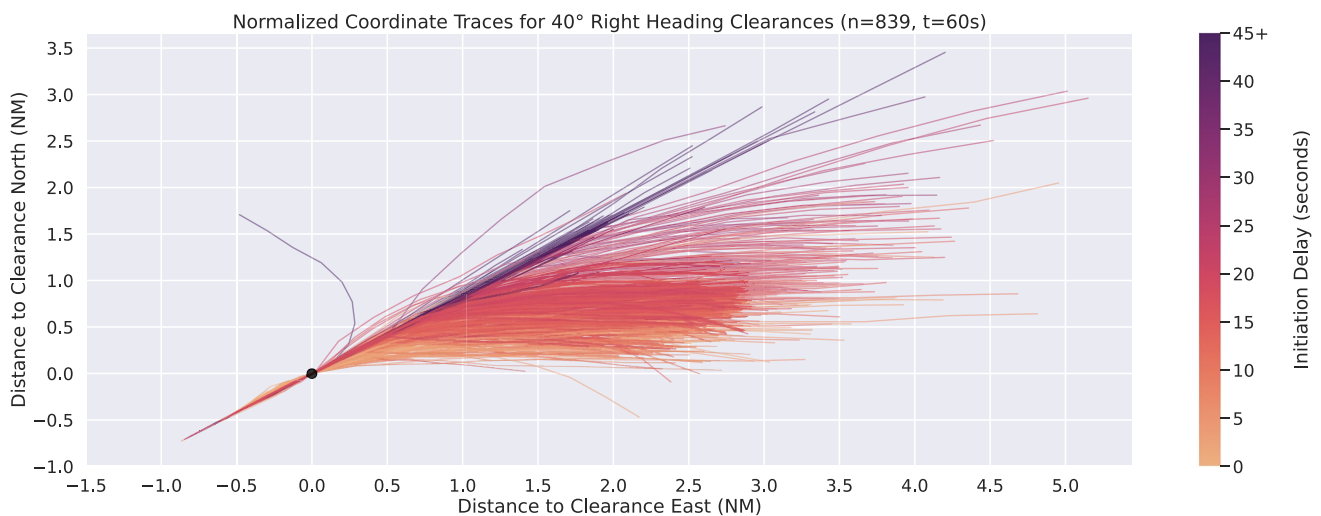


Fig. 1 Example trajectory divergence following an identical 40° right turn clearance issued to multiple aircraft. The significant difference in lateral positioning, following completion of the maneuver, highlights

the impact of differing pilot responses and maneuver execution on trajectory outcomes, motivating the need to understand response time factors

separation, and extend planning horizons. Therefore, understanding, quantifying, and potentially predicting the variability in pilot responses is a critical prerequisite for the safe and effective deployment of advanced digital ATC assistance systems.

Despite its importance, research quantifying pilot response times to ATC clearances using large-scale, real-world operational data remains limited. Existing studies often rely on smaller datasets, voice recordings, or simulation environments. This scarcity can be attributed to the difficulty in accessing integrated datasets containing both ATC clearances and corresponding flight data.

This paper addresses this gap by performing a detailed analysis of pilot initiation delays and maneuver completion times using the extensive Swedish Civil Air Traffic Control (SCAT) dataset. We focus on identifying key factors influencing these times and examining patterns in maneuver execution. Furthermore, we investigate the feasibility of predicting maneuver initiation delays and maneuver completion times using machine learning with the aim of providing a first baseline assessment of predictability based on operational data.

To summarize, our contributions are threefold:

- We analyze the distribution of pilot initiation delays and maneuver completion times for various types of ATC clearances using a large-scale real-world dataset (SCAT).
- We investigate the key factors influencing these times
- We investigate the predictability of initiation delay and maneuver completion time based on the identified factors across maneuver types

2 Related work

Understanding pilot response to Air Traffic Control (ATC) clearances is crucial for efficient and safe Air Traffic Management (ATM), particularly as systems evolve toward increased automation and AI integration. This chapter examines the current understanding of pilot response times to ATC clearances, factors that influence these times, and their implications for air traffic management. Additionally, we present our definitions for quantifying and predicting these response times.

2.1 Clearance response process and definitions

Figure 2 illustrates the sequence of events that make up a clearance and pilot response. When the ATCO makes the decision to issue a clearance based on the traffic information displayed by the Air Traffic Management (ATM) system, the clearance is issued to the pilot over a voice or data link channel. It is also simultaneously entered into the ATM system. Once the pilot receives a clearance, the clearance is then read back to the ATCO. Afterwards, the pilot initiates the cleared maneuver by controlling the aircraft. At fixed intervals, the aircraft transmits ADS-B data which is interpreted by the ATM system and displayed back to the ATCO.

Any given clearance can contain either a heading, altitude, or speed change instruction, or a combination of multiple instructions. For each measurement i , we calculate the **maneuver delta** as the difference between the instructed and the measured value as follows:

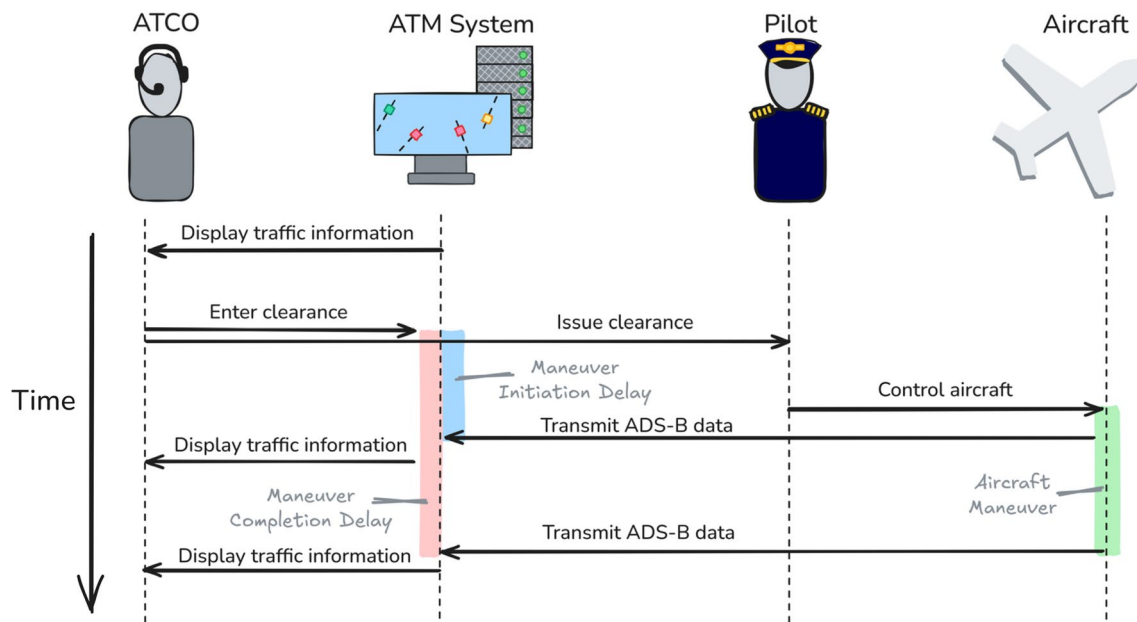


Fig. 2 The sequence of actions that lead to an issued clearance. Time progresses from top to bottom

$$\Delta_{\text{maneuver},i} = V_{\text{instructed}} - V_{\text{measured},i} \quad (1)$$

where:

- $V_{\text{instructed}}$ is the value (speed, heading, or level) instructed by the clearance
- $V_{\text{measurement},i}$ is the measured value thereof at measurement i after issuance

We view a **maneuver** as the time series of measurements where $|\Delta_{\text{maneuver},i}| < \Delta_{\text{tolerance}}$. Or in other words: A maneuver consists of all measurements where the absolute value of the maneuver delta is less than the maximum allowed tolerance. These tolerances differ per maneuver type:

- $\Delta_{\text{HEADING}} = 2.5$ deg
- $\Delta_{\text{SPEED}} = 5$ kts
- $\Delta_{\text{LEVEL}} = 1$ Flight Level

The values were chosen in accordance with the work by Lutz et al. [4], except for the speed tolerance, where we chose a larger tolerance to account for measurement inaccuracies present in the data. Furthermore, we call $\Delta_{\text{maneuver},0}$, the very first maneuver delta after the clearance issuance, the **initial maneuver delta**.

To measure the different delays of the process from clearance to successful execution, we define the following terms:

Initiation delay: The time between the clearance being issued and the first pilot reaction. This encompasses the time taken for the pilot to receive, process, and begin responding

to the clearance. The first pilot reaction is registered once 5% or more of the issued clearance delta is fulfilled.

Maneuver completion delay: The time between the issued clearance and the point where the aircraft has complied with the clearance with regard to all specified tolerances.

For the purposes of this analysis, we assume the recorded timestamp at which the clearance was entered into the Air Traffic Management system corresponds directly to the timestamp the clearance was issued. Furthermore, the underlying dataset used in this work does not specify whether a given clearance was issued via voice or data link; we assume a similar pilot response for both.

2.2 Evolution of pilot response time research

The quantification of pilot response times has evolved from basic communication metrics to comprehensive maneuver analysis. Early studies focused primarily on voice communication timings. Cardoso et al. [5] analyzed 508 en-route voice clearances by decomposing the process into controller transmission, silent processing time, and pilot readback, finding average readback delays around 3 s. While valuable for establishing communication baselines, these studies didn't capture the critical operational delay between clearance issuance and actual aircraft state change.

More recently, Lutz et al. [4] advanced the field by correlating voice data with aircraft trajectories near one airport, establishing two crucial metrics: initiation delay (time until maneuver begins) and maneuver completion time (total time

until clearance is fulfilled). Their findings revealed substantially longer operational delays than previously documented, with mean initiation delays of 20.7 s and completion times of 151.3 s. Importantly, they observed significant variations by clearance type. Heading changes (69.3 s) were completed much faster than altitude (176.1 s) or speed changes (182.3 s), highlighting that different maneuvers have inherently different execution profiles.

In a different context, Consiglio et al. [6] examined pilot responses to onboard system suggestions rather than ATC clearances, finding reaction times of 15.37 s for lower priority conflicts and 7.65 s for higher priority ones. This suggests that perceived urgency significantly influences response speed, a factor that may also apply to ATC clearances of varying operational priority.

2.3 Factors influencing pilot response times

Despite the importance of understanding what influences pilot response times, research specifically addressing this question remains limited. Several key factors have emerged from existing studies:

- **Clearance Type:** Lutz et al. [4] observed variations in response times based on clearance type (altitude, heading, or speed changes), with heading changes typically executed more quickly than altitude or speed adjustments.
- **Perceived Urgency:** As demonstrated by Consiglio et al. [6], the urgency of a situation can significantly affect response time, with pilots responding more quickly to higher priority situations.
- **Flight Phase:** Cardosi et al. [5] speculated that flight phase might influence response times, noting that their en-route findings might not apply to other phases of flight such as approach or departure.
- **Workload:** Literature on cockpit systems and pilot workload, such as Pritchett et al. [7], suggest that pilot workload significantly impacts task performance and response timing. Higher workload situations may result in increased response latency.

2.4 Impact on air traffic management systems

The significance of pilot response times for air traffic management is underscored by several studies. Rantanen et al. [8] simulated the effects of voice transmission delays and variable pilot response times on controller performance. Their findings indicated that increased variability in response times led to reduced accuracy in aircraft positioning and separation, highlighting the operational importance of predictable responses.

Vu et al. [9] approached this issue from a different angle, investigating how delayed responses from unmanned aircraft system (UAS) pilots affected controller acceptance. Their work emphasized the importance of timely responses for effective integration of new technologies into airspace management.

As ATM systems evolve toward greater automation and possibly AI integration, understanding and accurately predicting pilot response times becomes increasingly important for:

- Trajectory prediction accuracy
- Strategic conflict detection and resolution
- Efficient spacing and sequencing
- Workload management for controllers
- Overall system resilience and safety

2.5 Methodological approaches and research gap

Research on pilot response times has employed several methodological approaches, each with distinct advantages and limitations:

- **Voice Recording Analysis:** Studies like Cardosi et al. [5] and Lutz et al. [4] analyze voice recordings, providing rich contextual information but either suffering from errors in automated transcripts or requiring labor-intensive manual annotation which typically limits the sample sizes.
- **Human-in-the-Loop (HITL) Simulations:** Works by Consiglio et al. [6], Rantanen et al. [8], and Vu et al. [9] use controlled simulations that allow for experimental precision but may not fully capture real-world variability.
- **ATM System Data Analysis:** Our approach leverages clearance data directly from operational air traffic management systems. This methodology allows for large, diverse datasets without requiring voice transcription with the trade-off that some clearance context, transmitted in voice recordings, might be missing.

To the best of our knowledge, there are no previous works attempting to predict pilot response times based on historical ATM system data. Existing literature has primarily focused on measuring response times or examining influencing factors in controlled settings.

3 ADS-B data with ATCO clearances

3.1 Dataset

To analyse the pilot reactions to cleared maneuvers, we ideally need a large and diverse dataset. As the data collection

of clearances requires access to safety critical air traffic management systems, it is really hard to collect good data about issued clearances. To the best of our knowledge, the Swedish Civil Air Traffic Control (SCAT) dataset [10] is the largest and most comprehensive publicly available dataset that contains information about issued clearances with complementary ADS-B position data. This dataset consists of 13 weeks collected over a period of one year and contains a large amount of measurements from both en-route and Terminal Maneuvering Area (TMA) traffic. The dataset was collected over the Swedish airspace and provides detailed ADS-B and Mode-S data in 5 s intervals with corresponding clearances extracted from the Air Traffic Management system (Thales TopSky [11]), as well as additional weather and flight plan data. It, however, does not contain voice recordings or additional context for the clearances, which is important to bear in mind during further analysis. While the size and provided information are great, the unfiltered nature of SCAT brings along some challenges when working with the data. Therefore, we now go into detail about the preprocessing and filtering of the dataset.

3.2 Preparing the dataset

3.2.1 Initial cleaning of the data

Loading the SCAT dataset was greatly facilitated by using the traffic library [12]. After loading the clearances, we clean the data by analysing consecutive instructions and only keeping clearance instructions that deviate from the previously given instruction. For example when a clearance “*climb to flight level 300*” is followed by the clearance “*climb to flight level 300 and fly heading 100*”, only the additional heading change for the second clearance is kept. Without this processing step we were unable to obtain any heading or speed clearance without an additional level change in the entire dataset. In total we identified 1,187,437 clearances. We then filter these clearances and remove 72 clearances which do not include any instruction at all. Additional cleaning was conducted based on the reported measurements. 1459 flights contained an *unknown* category 62 “Mode of Movement” flag [13] for either vertical, translational or longitudinal movement, 42 flights reported neither altitude nor flight level. We excluded these flights to reduce exposure to measurement errors.

We also discovered that many flights do not broadcast their magnetic heading which we later need for analysing heading clearances. As these constituted more flights, instead of excluding, we calculate a magnetic correction factor which is applied to the track heading. The magnetic correction factor -2.944° was calculated by averaging all differences between track and magnetic headings

of aircraft reporting both. As all trajectories were captured over a roughly similar geographic area, this simple approach proved to be accurate enough for our use case, however it is worth keeping in mind that small inaccuracies for some aircraft reside.

3.2.2 Adding additional metadata

We now join the clearance data with the ADS-B position data and generate a unique clearance identifier that is used to identify individual clearances, the identifier is calculated by hashing the sum of the clearance timestamp and the unique flight identifier provided by SCAT.

For each clearance i , we calculate the **clearance age** for all measurements in a 15-minute forward looking window by subtracting the timestamp of issuance from the measurement timestamp:

$$\text{Age}_{c_i}(t) = t - t_{c_i \text{ issued}} \quad (2)$$

where:

- $\text{Age}_{c_i}(t)$ is the age of clearance c_i at time t
- t is the timestamp of the current measurement
- $t_{c_i \text{ issued}}$ is the timestamp clearance c_i was issued
- i is the index of the clearance being considered

We do this instead of simply considering the latest given clearance to account for clearances given before the previous maneuver is finished. This is particularly the case when considering instructed level changes. We then converted the altitude clearance values from ft to flight levels (FL) using standard atmospheric pressure. In some cases speed clearances were given in Mach instead of knots. As converting Mach to knots accurately requires atmospheric data not consistently available, all 14,475 clearances instructing speed only in Mach were excluded from further analyses. Speeds reported in knots were used directly.

We calculate the clearance speed delta for the instructed adjustment by subtracting the first measured speed after the clearance from the instructed speed value. A negative delta describes a speed reduction while a positive delta represents a speed increase. The same process is repeated for level and heading changes. Here, it should be noted that we always assume that the aircraft is turning in the shortest possible way, however for very large turns the ATCO can also request a turn with an additional turn direction, i.e. “*turn left heading 230*” which may lead to a longer flight path but avoids other traffic. As this event occurs rarely and the context is missing from the dataset, we chose to not investigate these cases further.

3.2.3 Filtering relevant clearances

By joining the clearance data with the ADS-B position data we already filtered all flights without any clearance. We further exclude all heading clearances to a beacon or navigation aid. These require additional context that is absent in the data and increase the processing complexity. Only 1808 of the 1,187,437 raw clearances are affected, so around 0.15%. For the remaining flights, the average clearance age was found to be more than three minutes, while the median is only around 3 s. After further investigation, we found that some outlier clearances were given long before the first position measurement was recorded. To focus on immediate pilot responses, we remove clearances from our analysis if the first recorded position data point for the flight appears 6 or more seconds after the clearance was issued. We chose 6 s to account for a slight clock drift. We also filter out all maneuvers which were not completed after a time of 15 min. Even though heading maneuvers are usually completed much faster, larger level changes can take upwards of ten minutes to complete, as we later show. After the described steps, we are left with the clearance counts shown in Table 1.

Looking at the resulting clearance counts per clearance type, we are left with 831,311 clearances. In total, 99 clearances thereof contain multiple instructions from which 80 clearances instruct a level and a speed change, another 10 for a level and a heading change, 4 clearances were made for a heading and speed change and 5 clearances were made for all level, heading and speed change combined. Due to the low amount of samples for multi-instruction clearances as well as the missing context we conclude that highlighting differences between single and multi-instruction clearances without additional information would not be appropriate. Therefore, we focus on the single instruction clearances only.

Table 1 Count of clearances per clearance type after all described preprocessing and filtering steps

Clearance Type	Count
Level Change	634276
Heading Change	116498
Speed Change	80438
Level + Heading	10
Level + Speed	80
Level + Heading + Speed	5
Heading + Speed	4

4 Analysis of maneuver completion times

This chapter analyzes maneuver completion times in air traffic control, focusing on how pilots respond to different types of clearances. We examine initiation delays and completion times, looking at how they relate to various flight conditions. The analysis covers overall trends across all clearance types, as well as specific details for heading changes, level changes, and speed adjustments. By studying these aspects, we aim to understand the factors that influence how quickly and effectively pilots carry out air traffic control instructions.

4.1 Cumulative analysis

When plotting the initiation delay in Fig. 3, we observe a right-skewed distribution with a peak at 10.75 s and a pronounced tail extending beyond 60 s. This pattern is consistent with typical human reaction time measurements observed across various domains. In our calculation, including all initiation delays below 90 s, the mean initiation delay is 20.50 s while the histogram maximum is at 10.75 s. When comparing these results with the 20.7 s total initiation delay average calculated by Lutz et al. [4], this matches their results closely. When including all initiation delays up to 900 s the values were several minutes higher.

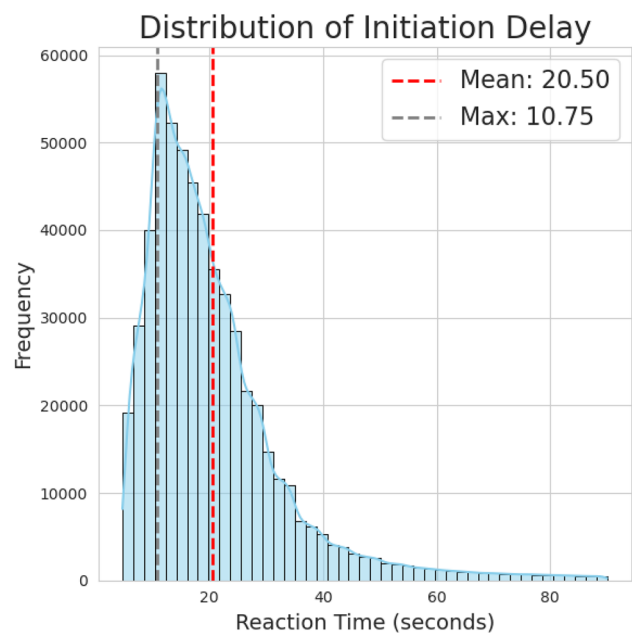


Fig. 3 Histogram of initiation delays for all clearance types

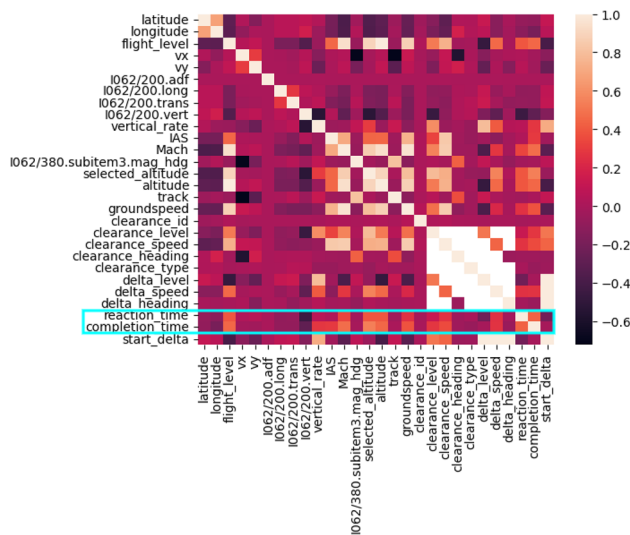


Fig. 4 Correlation matrix between all observed measurements and derived values recorded at the time at which the clearance was issued. Initiation delay and completion time are correlated with the flight level and ground speed. See Appendix A for a short description of the depicted measurement values

To further investigate the contributing factors, we next looked at the correlation matrix between all recorded numeric values for each clearance response shown in Fig. 4.

It can be seen that the reaction and completion time are highly correlated which is not surprising. The completion time is correlated with the vertical rate at the time of the clearance. This is also expected as aircraft flying a vertical maneuver are more likely to receive another level change clearance and can complete this maneuver faster when already in motion compared to aircraft in level flight. What is more interesting is the observation that a strong correlation between the initiation delay and the aircraft flight level at the moment of the clearance exists. The same holds true for the aircraft's speed.

4.1.1 Analysis by flight level

Once we plot the initiation delay per clearance type and per flight level, as shown in Fig. 5, we can observe a consistent pattern across all flight levels: level change clearances generally result in the longest initiation delays, followed by speed change instructions, while heading change commands consistently produce the quickest responses from pilots. Interestingly, the data also reveals a clear trend in initiation delays across flight levels. Lower altitudes (0–50, 50–100) exhibit shorter overall delays across all clearance types, while higher altitudes (300–350, 350+) demonstrate the longest initiation delays, particularly for level change and speed change clearances. One possible explanation for the pattern could be the different levels of alertness per flight level. Lower levels are

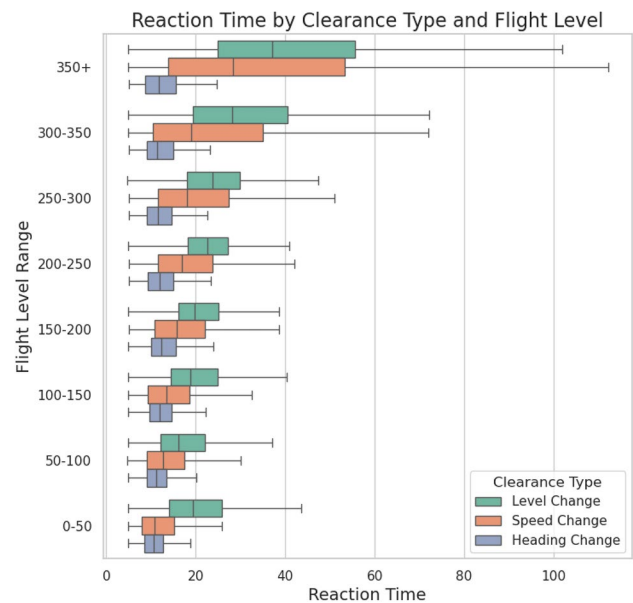


Fig. 5 Pilot initiation delays to different air traffic control instruction types across various altitude ranges. The width of each box represents the quartiles of the distribution, the bars show the outlier-filtered minimum and maximum values

typically associated with takeoff and landing phases, where a sense of urgency and heightened alertness may lead to quicker pilot responses. Conversely, higher altitudes often correspond to cruise phases, where pilots may be engaged in other tasks or experiencing reduced alertness due to the routine nature of this flight segment. The differences between different clearance types need to be viewed with care, as our methodology of measuring maneuver completion time based on a 5% completion can skew the resulting initiation delays for very large maneuvers. Nonetheless, in general, heading changes are often regarded as more time critical because a delayed adherence to the instruction could result in longer routes and thus additional time and fuel consumption, while a slower climb, descent or speed change do not necessarily have the same effect.

4.1.2 Differences in Maneuver execution

Figure 6 illustrates 100 traces of different pilot responses for level, heading, and speed clearances, with dotted lines indicating the target area of the issued clearance within defined tolerances.

Level changes show consistent linear trends, suggesting constant climb and descent rates per aircraft. Larger altitude changes exhibit steeper slopes, suggesting higher vertical speeds for substantial level adjustments. Most clearances instruct the pilot to descend (negative delta). Heading changes are executed much more rapidly, usually within 50 s, aligning with earlier observations of quick

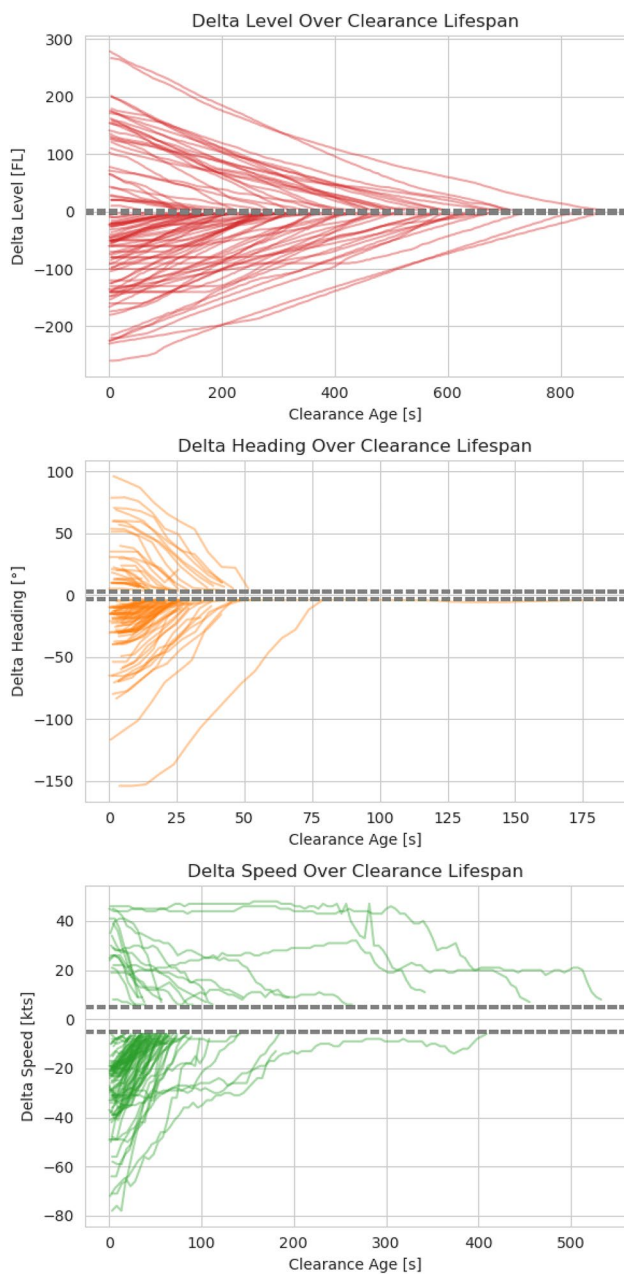


Fig. 6 Illustration of 100 different relative pilot reactions to given clearances. The dotted lines represent the tolerances for completion as discussed in chapter 2.1

pilot initiations. Most adjustments fall within ± 50 degrees, with similar turn rates regardless of the clearance magnitude. Speed adjustments take 200–300 s on average, falling between heading and level changes in duration. Changes mostly range within ± 40 knots, showing much more variety, possibly due to engine performance or wind conditions influencing the maneuver. Further analysis could correlate these patterns with aircraft type, flight phase, and airspace complexity.

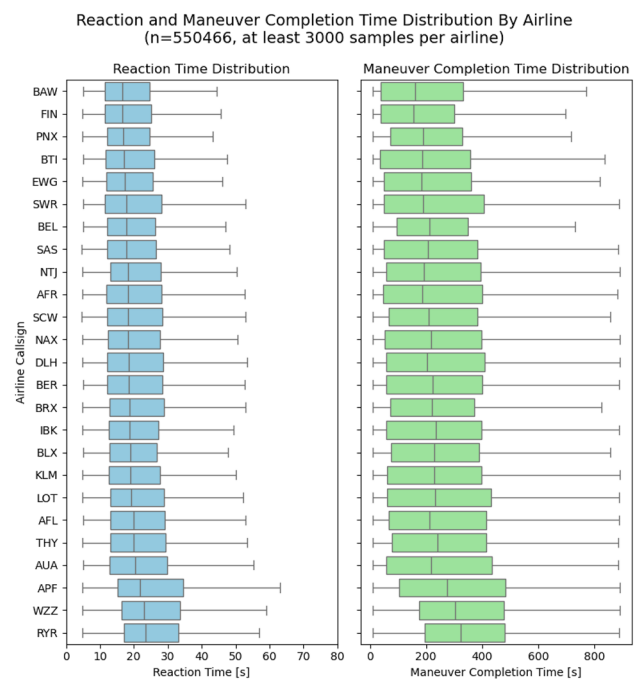


Fig. 7 Comparison of pilot initiation delay and maneuver completion time across airlines

4.1.3 Analysis by categorical values

We now analyse the impact of categorical values not present in the correlation matrix. Most interestingly, the pilot initiation delay shown in Fig. 7 differs slightly per airline, which we extracted from the flight's callsign.

The values have a large variation, which is also amplified by the measurement resolution of 5 s, however due to the large number of samples per airline and in total we can see an approximate order. The depicted order was determined by the median initiation delay, however the median maneuver completion time order is almost similar. The delta between the fastest and slowest median initiation delay is around 5 s which represents 20%. Notably, the low cost carrier airlines “Ryanair” and “WizzAir” as well as the Swedish cargo airline “Amapola Flyg” had a higher initiation delay. The fastest median responses were recorded by “British Airways” and “Finnair”. Figure 8 shows the distributions for each aircraft type. Noticeably, the smaller aircraft “Embrayer E145” and “ATR 72” took slightly longer to start and to complete the maneuvers. In general, however, the differences are only small and not conclusive (Fig. 9).

4.1.4 Analysis by time of day

If we look at the reaction times per hour of the day in Fig. 10, it can be observed that between 21:00 and 04:00 the reaction time is visibly longer between 10 and 20% on average,

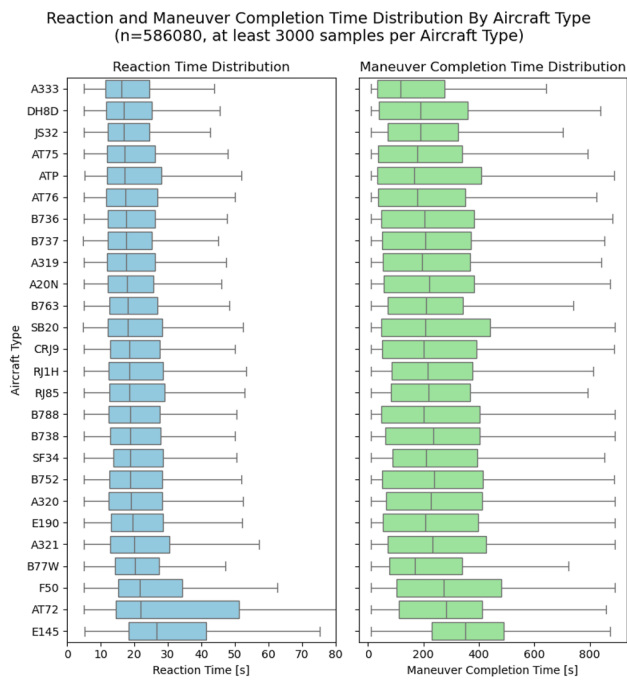


Fig. 8 Comparison of pilot initiation delay and maneuver completion time across aircraft types

similar results were obtained for the maneuver completion times. This variation could be attributed to several factors. Most airports have limited operations during these hours, leading to lower traffic density and a higher percentage of en-route flights, which typically have longer reaction times

as shown in our flight level analysis. Additional possible influencing factors could include the pilots' alertness levels and workload patterns throughout a 24-hour period.

4.2 Analysis per clearance type

For each clearance type, we conduct a separate analysis. Our approach begins with visualizing and interpreting the distribution of initial maneuver deltas. Following this, we evaluate the maneuver completion times, considering how they relate to the varying levels of the initial maneuver delta observed.

4.2.1 Heading changes

We now look at the overall distribution of issued heading change clearances by the ATCOs, we can clearly see a pattern.

Figure 11a illustrates how the split between left turns (negative delta) and right turns (positive delta) is roughly similar. We can see that smaller heading corrections are cleared more often than large turn maneuvers. Turns with a 100 degree delta or more are under-represented in the dataset. Additionally, we can clearly see large spikes in the distribution. These correspond to heading deltas divisible by 10: 10, 20, 30, etc.. We can also see smaller spikes for all deltas in between at 15, 25 and 35. This is likely related to relative turn clearances influenced by ATCO training, procedures or limitations enforced by the ATM system. Other values are possible to achieve

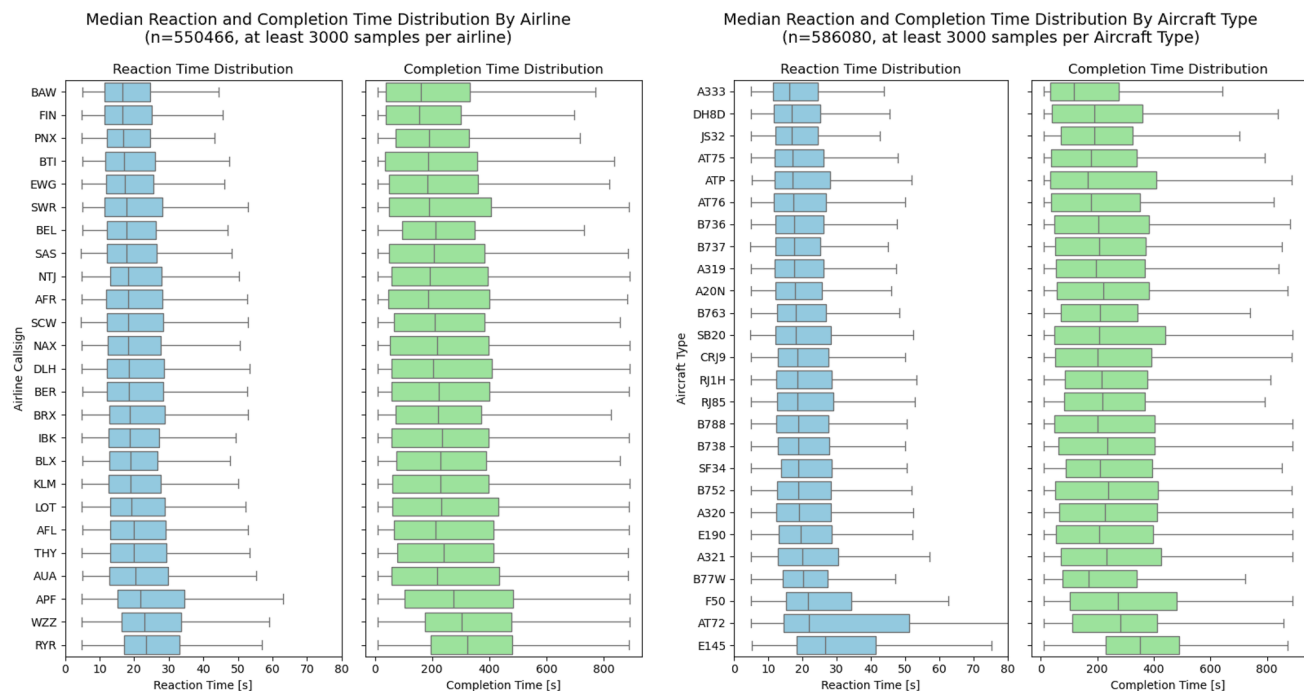


Fig. 9 Comparison of pilot initiation delay and maneuver completion time across airlines and aircraft types

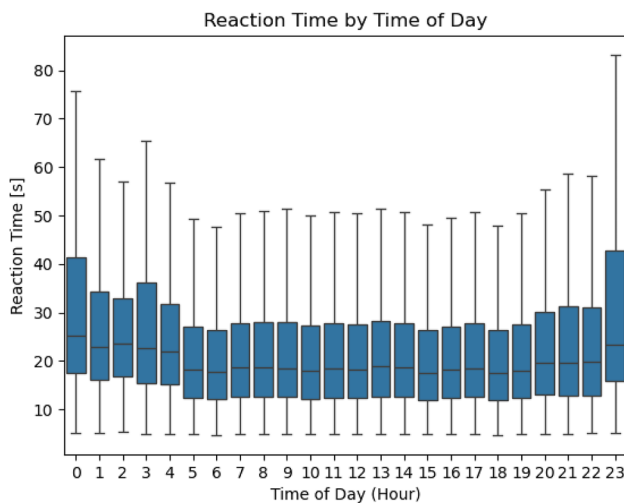


Fig. 10 The initiation delay per hour of the day. On average pilots respond slower between 21:00 and 04:00

by clearing absolute heading values, e.g. “fly heading 310”, while the aircraft is flying a course outside of the described discretization.

Another important relationship to understand is the one between maneuver complexity and maneuver completion time. The maneuver completion time is calculated to be the duration between the issued clearance and the successful completion of the cleared maneuver, as explained in chapter 2. A fast maneuver completion time could offset a slow pilot reaction. For example, this is the case when pilot *A* takes longer to react than pilot *B* but *A* flies a sharper turn, both *A* and *B* could end up in the same end state after the maneuver. If we now look at the maneuver completion time for the different heading maneuver complexities shown in Fig. 12, we can see a clear relationship where larger turns take longer to complete. The relationship seems to be quadratic and symmetrical. We can also see vertical lines corresponding to the deltas with headings divisible by ten, as discussed before.

4.2.2 Level changes

Looking at the distribution of relative level change clearances in Fig. 11c, we can see that most level change clearances clear the aircraft to descend, most clearances are between -20 and -100 flight levels.

The spikes in the distribution, similarly to the distribution of heading changes, show a resolution in the clearances. We also observe some clearances with an absolute delta of more than 200 flight levels which is likely issued in low traffic areas where an aircraft can be cleared to climb or descend without any risk of causing a conflict. As the dataset was collected over the Swedish airspace where especially the northernmost parts are sparsely populated, this seems plausible but the spread will likely differ in regions with higher traffic density. Interestingly, descent commands are concentrated between -100 and -20 flight levels, while climb commands are spread over 0 – 200 flight levels. This difference may be due to the nature of approach and departure procedures. Multiple smaller clearances during descent could be attributed to the need for more precise control as aircraft enter congested terminal airspace and prepare for landing. In contrast, departing aircraft may receive fewer, larger clearances as they quickly climb to cruising altitude in less restricted airspace.

For level change clearances, like with the issued heading clearances, a clear correlation arises and is shown in Fig. 13. As seen in Fig. 11c, the cleared level change deltas for descent clearances show peaks at flight levels deltas divisible by 10. For climb clearances this is likely not the case because the aircraft is not at level flight when receiving the clearance, therefore the cleared level may have a fixed step resolution but the level delta does not. The relationship is approximately linear for larger deltas though very small level changes have an associated overhead. When fitting a regression line, the average descent rate was approximately 2600 ft/min while the average climb rate is slightly lower at around 2300 ft/min.

Fig. 11 Histograms of cleared heading, speed, and level changes above specified thresholds

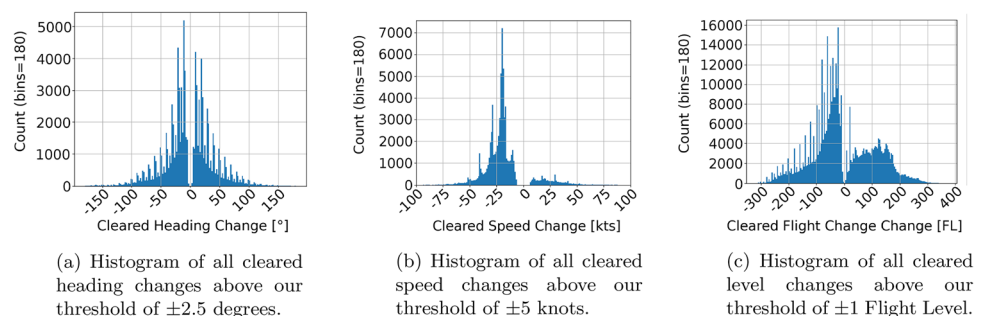


Fig. 12 Heading maneuver completion times depending on the initial maneuver delta. A negative delta corresponds to a left turn

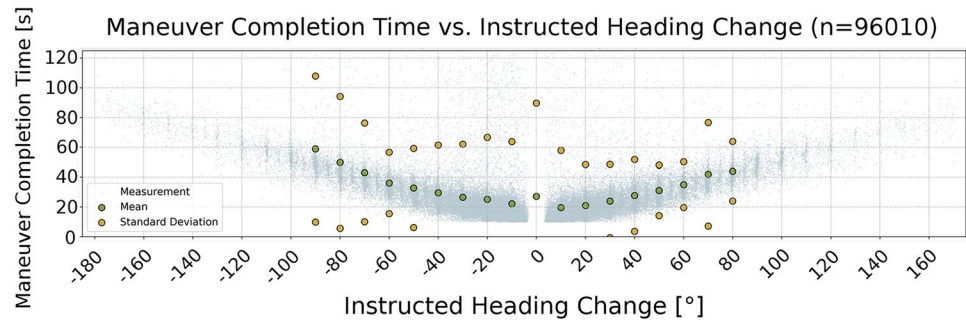


Fig. 13 Flight level clearance maneuver completion times depending on the cleared level delta. A negative delta corresponds to a descent

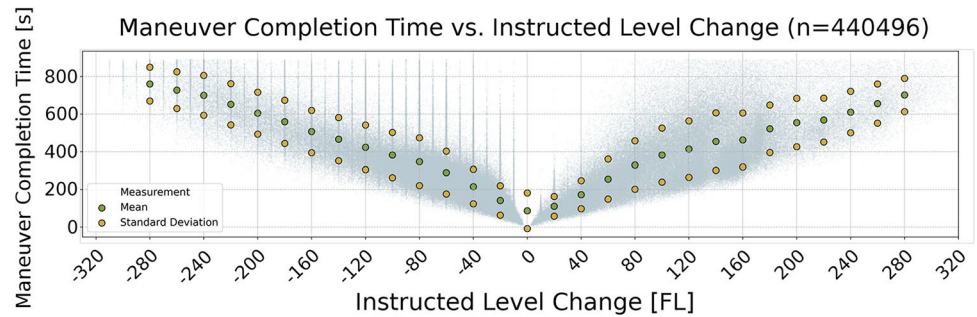
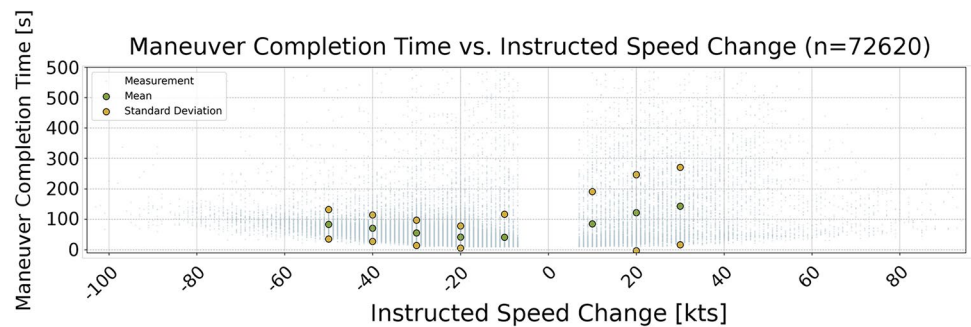


Fig. 14 Speed change clearance maneuver completion times depending on the cleared speed delta. A negative delta corresponds to a speed reduction



4.2.3 Speed changes

The distribution of speed change clearances shown in Fig. 11b is interesting as the clearances do not follow a Gaussian or uniform distribution. Instead the instruction to decrease the speed by 20 knots is by far the most common clearance. In fact, the data indicates that around a third of clearances instructed a change between -18 and -22 knots. The other spikes correspond to a reduction by 30 knots and by 40 knots. Furthermore, only 10% of clearances cleared the pilots for a speed increase. As with the level change clearances, the count of this specific maneuver is likely influenced by ATCO training and specific sector properties. Combined with the level change clearance distribution, we can also assume that landing aircraft received more clearances than departing aircraft.

The completion times for speed changes in Fig. 14 are slightly longer when larger deltas are cleared, however it looks much less correlated compared to level and heading

changes. This aligns with our findings before and Fig. 6 illustrates the large variety in speed changes.

Table 2 Model performance metrics for different clearance types

Clearance type	Metric	Completion time	Initiation delay
Level	R^2 ($\uparrow$)	0.8241	0.01
	RMSE (s) ($\downarrow$)	80.5281	341.3661
	MAE (s) ($\downarrow$)	44.0879	293.7840
	MAPE (%) ($\downarrow$)	12.77	87.01
Speed	R^2 ($\uparrow$)	0.7642	0.1687
	RMSE (s) ($\downarrow$)	33.1310	62.1048
	MAE (s) ($\downarrow$)	19.1092	39.6689
	MAPE (%) ($\downarrow$)	35.96	63.44
Heading	R^2 ($\uparrow$)	0.7302	0.2394
	RMSE (s) ($\downarrow$)	18.4355	32.4578
	MAE (s) ($\downarrow$)	13.4641	14.9147
	MAPE (%) ($\downarrow$)	55.78	43.45

5 Predictability of pilot response times

A core requirement for digital Air Traffic Control Officer (ATCO) systems is accurately predicting aircraft response to clearances. This section presents our investigation into the predictability of both maneuver completion time and initiation delay, analyzing these components separately. We employed AutoGluon [14] to build predictive models for each component using the five most influential features identified in our analysis:

- initial maneuver delta
- flight level
- vertical rate
- speed
- time of day

For each of the two prediction tasks, the dataset was divided into 70% training, 10% validation, 20% testing. The reported results are calculated on the test set (Table 2).

Our analysis reveals a distinct predictability divide between maneuver components. Completion time demonstrates robust predictability (R^2 values above 0.73 for all clearance types), indicating that aircraft performance characteristics largely govern execution once a maneuver begins. Conversely, initiation delay shows limited predictability, with level changes showing particularly challenging characteristics. This predictability difference likely stems from completion time being governed primarily by physics and aircraft capabilities, while initiation delay appears influenced by human factors beyond our current feature set. When interpreting MAPE values across different maneuver types, it's important to consider that they are influenced by typical maneuver durations. Heading maneuvers, which typically complete faster than level changes, show higher completion time MAPE despite better absolute error metrics, simply because small absolute errors represent larger percentage errors in shorter-duration maneuvers.

The strong predictability of maneuver completion times means these systems can reliably forecast aircraft trajectories once pilots initiate a response. However, the poor predictability of initiation delays creates a significant uncertainty window that digital systems must accommodate. This uncertainty could limit how far in advance automated systems can plan conflict-free trajectories and may require implementation of conservative safety buffers. Future work could explore comparing our statistical approach with physics-based aircraft performance models, or potentially combining both methodologies to create a hybrid system that leverages the strengths of each approach for more accurate and robust predictions across different flight phases and conditions.

6 Conclusion

This study provides a comprehensive analysis of pilot response times to air traffic control clearances using the large-scale, real-world SCAT dataset comprising approximately 830,000 clearances. Our investigation aimed to quantify and predict both initiation delays and maneuver completion times to reduce uncertainty in trajectory predictions for future digital ATC systems.

Our analysis revealed that pilot reaction times follow a right-skewed distribution with a mean initiation delay of 20.5 s. We identified several significant factors influencing response behaviors:

- **Flight Level:** A strong correlation exists between altitude and response times, with lower altitudes (0–100 FL) exhibiting significantly shorter reaction times compared to higher altitudes (300+ FL), likely due to different flight phases and associated pilot alertness levels.
- **Clearance Type:** Consistent patterns emerged across maneuver types, with heading changes eliciting the quickest responses, followed by speed changes, while level changes resulted in the longest reaction times.
- **Time of Day:** Initiation delays differ by 10–20% depending on the time of day.
- **Initial Maneuver Delta:** Initial maneuver delta significantly influenced completion times, with larger heading and level changes requiring proportionally more time to execute, following predictable patterns.
- **Secondary Factors:** While slight variations in response times across different airlines and aircraft types were observed, these differences were not statistically significant compared to the aforementioned factors.

Our predictive modeling results demonstrate a clear distinction between the predictability of the two maneuver components. Completion times showed strong predictability (R^2 values above 0.73 for all clearance types). In contrast, initiation delays proved more challenging to predict accurately, suggesting that additional human factors not captured in our feature set significantly influence when pilots begin executing clearances. The methodology we developed for analyzing and predicting pilot response characteristics can be generalized to other airspaces and datasets containing similar clearance and trajectory information, though specific values may vary based on regional factors such as airspace complexity, traffic density, and local procedures.

Several limitations should be acknowledged. The SCAT dataset, while extensive, lacks voice recordings and contextual information about clearance urgency or rationale. Additionally, our methodology for measuring completion

based on defined tolerances may introduce slight variations based on the thresholds selected.

These findings have important implications for air traffic management systems, particularly those incorporating AI-based decision-making. The strong predictability of maneuver completion times provides a foundation for digital ATC systems to accurately forecast aircraft trajectories once pilots initiate a response, while the uncertainty in initiation delays highlights a critical area requiring conservative safety considerations. This understanding can inform more efficient clearance strategies and potentially reduce controller workload.

Future research could focus on investigating other influencing factors, particularly for initiation delays, through incorporation of additional contextual factors such as clearance urgency, conflict resolution requirements, and voice communication characteristics. The maneuver completion prediction could be compared to physical aircraft models. Additionally, the approach could be combined with synthetic data generation techniques [15] to transfer this approach to other datasets. We plan to integrate these findings into DLR's digital ATCO system that collaborates with human controllers [2, 3] through human-autonomy teaming.

Description of measurements shown in figure 4

This appendix provides definitions for the key values used throughout the analysis of pilot response times, for a more detailed description of all values, refer to the SCAT paper [10] and the CAT62 standard [13].

- `latitude`: Geographical latitude of the track.
- `longitude`: Geographical longitude of the track.
- `flight_level`: Reported flight level of the aircraft (I062/136).
- `vx`: Calculated ground speed component (X-direction, I062/085).
- `vy`: Calculated ground speed component (Y-direction, I062/085).
- `I062/200.adf`: Altitude Discrepancy Flag (Mode of Movement, I062/200).
- `I062/200.long`: Longitudinal Mode of Movement (Constant/Increasing/Decreasing Speed, I062/200).
- `I062/200.trans`: Transversal Mode of Movement (Constant Course/Left/Right Turn, I062/200).
- `I062/200.vert`: Vertical Mode of Movement (Level/Climb/Descent, I062/200).
- `vertical_rate`: Calculated rate of climb/descent (I062/155).
- `IAS`: Indicated Air Speed (from I062/380).
- `Mach`: Mach number (from I062/380).

- `I062/380.subitem3.mag_hdg`: Magnetic Heading (from I062/380).
- `selected_altitude`: Pilot selected altitude (MCP/FCU, from I062/380).
- `altitude`: Reported altitude of the aircraft (I062/135).
- `track`: Calculated track angle (ground direction, from I062/080).
- `groundspeed`: Calculated speed over ground (from I062/080).
- `clearance_id`: Unique identifier for the ATC clearance instance (Derived).
- `clearance_level`: Instructed flight level in the ATC clearance.
- `clearance_speed`: Instructed speed (kts) in the ATC clearance.
- `clearance_heading`: Instructed heading (deg) in the ATC clearance.
- `clearance_type`: Category of ATC clearance (Level, Speed, Heading, Combo) (Derived).
- `delta_level`: Initial difference: instructed level-measured level (See Sect. 2.1).
- `delta_speed`: Initial difference: instructed speed-measured speed (See Sect. 2.1).
- `delta_heading`: Initial difference: instructed heading-measured heading (See Sect. 2.1).
- `reaction_time`: Time from clearance issuance to start of maneuver (Initiation Delay, see Sect. 2.1).
- `completion_time`: Time from clearance issuance to maneuver completion (Maneuver Completion Delay, see Sect. 2.1).
- `start_delta`: Initial difference between instructed and measured value at issuance (Initial Maneuver Delta, see Sect. 2.1).

Author contributions N.W. came up with the idea, authored the main manuscript and implemented the proposed approach. J.R. contributed to writing Section 2 and offered valuable insights into the domain context. D.Z. created figures 10, 11, 12 and made meaningful contributions to the implementation. M.J. provided critical feedback on the manuscript's writing and structure, helped to rewrite Section 6 and suggested the use of the SCAT dataset for this research. S.S.-M. offered valuable insights into the domain context and played a key role in defining the research trajectory. All authors reviewed and approved the final manuscript.

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Data Availability The used SCAT dataset is openly available to the public at the following URL: <https://data.mendeley.com/datasets/8yn985bwz5/1>.

Declarations

Conflict of interest The authors have no conflict of interest to declare that are relevant to the content of this article.

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References

1. Degas, A., Islam, M.R., Hurter, C., Barua, S., Rahman, H., Poudel, M., Ruscio, D., Ahmed, M.U., Begum, S., Rahman, M.A., Bonelli, S., Cartocci, G., Di Flumeri, G., Borghini, G., Babiloni, F., Aricó, P.: A survey on artificial intelligence (ai) and explainable ai in air traffic management: Current trends and development with future research trajectory. *Appl. Sci.* **12**, 3 (2022). <https://doi.org/10.3390/app12031295>
2. Jameel, M., Tyburzy, L., Gerdes, I., Pick, A., Hunger, R., Christoffels, L.: Enabling digital air traffic controller assistant through human-autonomy teaming design. In: 2023 IEEE/AIAA 42nd Digital Avionics Systems Conference (DASC), pp. 1–9 (2023)
3. Gerdes, I., Jameel, M., Hunger, R., Christoffels, L., Gürlük, H.: The automation evolves: Concept for a highly automated controller working position. In: 33rd Congress of the International Council of the Aeronautical Sciences, ICAS 2022. ICAS (2022). <https://elib.dlr.de/190172/>
4. Lutz, M., Chatterji, G.B., Idris, H.R.: Characterization of response times based on voice communication and traffic surveillance data. In: AIAA AVIATION 2022 Forum, p. 3762 (2022)
5. Cardosi, K.M., Boole, P.W.: Analysis of pilot response time to time-critical air traffic control calls. United States. Department of Transportation. Federal Aviation Administration, Technical report (1991)
6. Consiglio, M.C., Wilson, S.R., Sturdy, J., Murdoch, J.L., Wing, D.J.: Human in the loop simulation measures of pilot response delay in a self-separation concept of operations. In: 27th Congress of the International Council of the Aeronautical Sciences (ICAS) (2010)
7. Pritchett, A.R., Vandro, B., Edwards, K.: Testing and implementing cockpit alerting systems. *Reliab. Eng. Syst. Saf.* **75**(2), 193–206 (2002)
8. Rantanen, E.M., McCarley, J.S., Xu, X.: Time delays in air traffic control communication loop: effect on controller performance and workload. *Int. J. Aviat. Psychol.* **14**(4), 369–394 (2004)
9. Vu, K.-P.L., Chiappe, D., Morales, G., Strybel, T.Z., Battiste, V., Shively, J., Buker, T.J.: Impact of UAS pilot communication and execution latencies on air traffic controllers' acceptance of UAS operations. *Air Traffic Control Quart.* **22**(1), 49–80 (2014)
10. Nilsson, J., Unger, J.: Swedish civil air traffic control dataset. *Data Brief* **48**, 109240 (2023)
11. Group, T.: TopSky - ATC — thalesgroup.com. <https://www.thalesgroup.com/en/markets/aerospace/air-traffic-management/topsky-atc>. [Accessed 03-09-2024]
12. Olive, X.: traffic, a toolbox for processing and analysing air traffic data. *J. Open Sour. Softw.* **4**, 1518 (2019)
13. EUROCONTROL: Cat062 - eurocontrol specification for surveillance data exchange asterix part 9 category 062. Technical report, EUROCONTROL (February 2023). System Track Data - Edition 1.20. <https://www.eurocontrol.int/sites/default/files/2023-02/asterix-cat062-system-track-data-p9-ed1-20.pdf>
14. Erickson, N., Mueller, J., Shirkov, A., Zhang, H., Larroy, P., Li, M., Smola, A.: AutoGluon-tabular: robust and accurate automl for structured data. arXiv preprint [arXiv:2003.06505](https://arxiv.org/abs/2003.06505) (2020)
15. Renkhoff, J., Wüstenbecker, N., Jameel, M., Schier-Morgenthal, S.: Automated data labeling for air traffic control: Predicting clearances from ADS-B data. In: DLRK 2024 Deutscher Luft- und Raumfahrtkongress, Lilienthalplatz 7, 38108 Braunschweig, Germany (2024). German Aerospace Center (DLR). To be published

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