TIL Phyton Programming

Exploratory Analysis of Climbing Behaviour of Selected Airbus Aircrafts

Source: aerotask.de

Authors

Student	Number
Stefan Huber	6306861
Bryan Inggas	5286654
Paul Kloos	6305245
Kai Müller	6306101
Mega Pradipta Fainallazi	6068308

Delft, November 8, 2024

Course: TIL6022

Contents

1 Introduction **2**

2 Data Preparation **3**
2.1 Selection of Departing Airports . . . 3
2.2 Data Preprocessing for Analysis . . . 3

3 Q1: Velocity over Time during Climb Phase **5**

4 Q2: Altitude Change over Time during Climb Phase **7**

5 Q3: Climb Rate Change over Time **8**
5.1 Calculating the Climb Rate . . . 8
5.2 Analysis of the Climb Rate . . . 8
5.2.1 Conclusion . . . 11
5.3 Comparison of Q3 to the Climb Rate Change over Barometric Altitude . . . 12

6 Q4: Factors Contributing to Deviations from the Defined Optimal Climb Rate **15**
6.1 Correlation Analysis . . . 15
6.2 True Air Speed . . . 15
6.3 Temperature . . . 17

7 Conclusion **18**

8 Contribution Statement **19**

Literature **20**

A Appendix **21**

1 Introduction

This exploratory report investigates how different aircrafts behave during the climbing phase, focusing on the factors that influence these changes. By focusing on the performance of aircrafts departing from two major Paris airports, Charles de Gaulle and Orly, the study ensures a controlled environment that allows a more accurate comparison between different aircraft models. The dataset includes multiple flights for each model and provides a solid basis for analysing trends and variations in speed, altitude and climb rate over time.

The main research questions include the investigation of speed changes during the climb phase (Q1), the understanding of altitude fluctuations over time (Q2) and the investigation of climb rate dynamics (Q3). In addition, the study investigates the factors that contribute to deviations from an optimal climb rate, taking into account aspects such as airspeed, temperature and mission profile (Q4).

The report uses Python programming to pre-process, analyse and visualise data, providing insights into model-specific behaviour and performance variations at different altitudes. By analysing the characteristic patterns of each aircraft model, the study aims to provide actionable insights into the performance characteristics of the aircraft.

For the analysis, aircraft models were narrowed down to a selection of short-range to long-range designs manufactured by Airbus SE. Figure 2 shows an overview of these aircrafts. The A320 Family hosts a variety of narrowbody / short- to medium-haul aircraft, namely the A319, the A320 and the A321. The A330-200 (also named: A332) has been selected to represent the widebody / long-haul aircraft. From left to right the aircrafts increase in 1. size (34 m - 59 m), 2. weight (75,5 t - 234,0 t), 3. thrust (213 KN - 640,5 KN) and 4. capacity (124 PAX - 250 PAX) but decrease in optimal climb rate (900 m/s - 650 m/s).

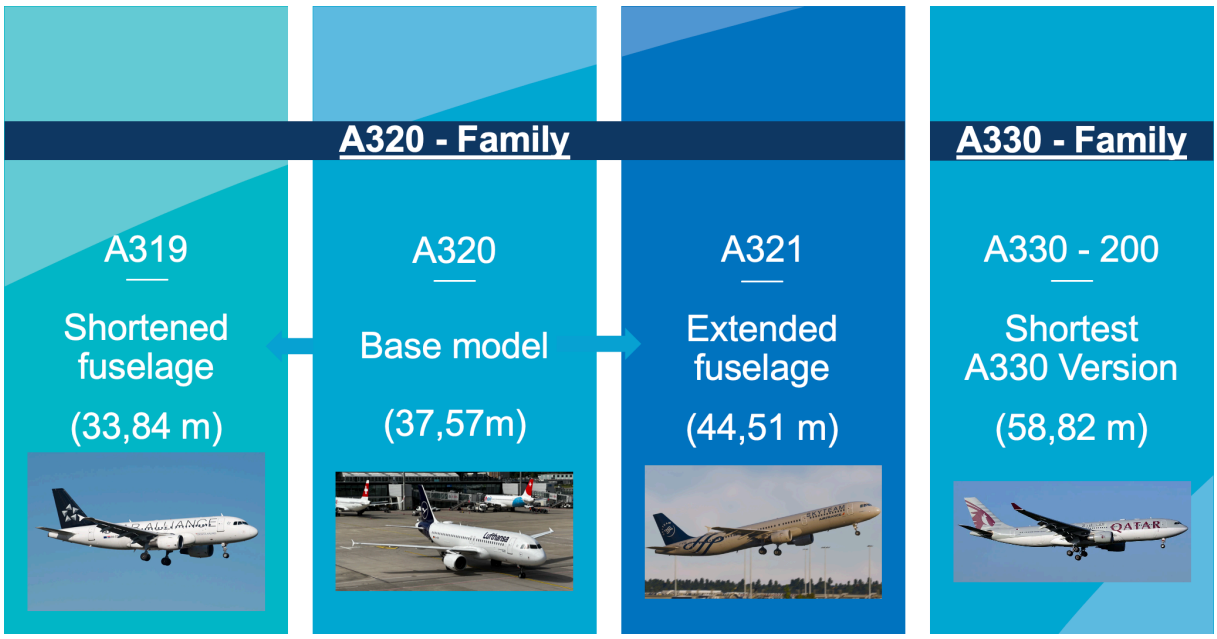

Figure 2: Overview of Aircraft types

Data for this research has been gathered from OpenSky and displays flights from the year 2017. (OpenSky-Network 2024)

2 Data Preparation

2.1 Selection of Departing Airports

Background: To make the data more comparable and reliable, the decision has been taken to focus on one location as potential influencing factors are similar.

1. Removing `timestep > 0` from all four data files.
   Assumption: The location of the aircraft is closest to the airport at `timestep = 0`.
2. Grouping all the lat/lon values to identify common locations by rounding to the first decimal point.
   Assumption: There are no major airports within the same 0.1° lat and lon (depending on the locations, this means a distance of 5-10 km).
3. Quantifying the flights of each aircraft to determine which locations host the most departures for each aircraft type. Locations where not all aircraft types occurred were removed.
4. Verifying each location to assign the airport to the coordinates.
5. Choosing Paris due to the highest number of departures for each aircraft type.
6. In the visualization, it was found that two major airports in Paris host all the aircraft types. To increase the amount of data and its robustness, the decision was made to consider both airports, *Charles de Gaulle* and *Orly*.

2.2 Data Preprocessing for Analysis

The following section outlines how the csv.xz files were processed to make them suitable for addressing the research questions. Initially, the necessary libraries, such as pandas and lzma, were loaded to facilitate the data handling process.
After the evaluation of the columns in the files, we decided to include the following in our dataframes:

- time: Timestamp of the measurement
- timestep: Time intervals of the measurements, with increments of 15 seconds
- maxtimestep: Total duration of measurements for each flight
- *icao24*: Unique aircraft identifier (coding standard differ from public's code)
- *callsign*: Identification sequence used for ground communication
- baroaltitude: Barometric altitude of the aircraft at the time of measurement
- lat: Latitude coordinate
- lon: Longitude coordinate
- velocity: Ground speed of the aircraft
- *segment*: Represents an individual takeoff event
- *modeltype*: Aircraft model type
- *operator*: Flight operator
- vertraratecorr: Corrected vertical climb rate
- *fromICAO*: Departure airport identifier (coding standard differ from public's code)
- *toICAO*: Destination airport identifier (coding standard differ from public's code)
- distance_from_dep: Distance from the departure airport at the time of measurement
- trip_distance: Total distance of the flight
- temp: Temperature at the time of measurement

- tas: True Air Speed, velocity relative to wind conditions

However, the majority of the data in each dataset has been standardized. For instance, all aircraft departing from the same airport (fromICAO) were assigned a uniform identifier, making it impossible to trace the actual airport. The same standardization was applied to the parameters highlighted in italics above. Given its role in uniquely identifying individual flights, the "segment" column was utilized as the index. At first glance, it seemed logical to use "vertraratecorr" for our calculations. However, due to the lack of information regarding the methodology behind the correction, we decided to calculate our own climb rate.

As described in 2.1, only flights within the geographical area surrounding Paris were considered. To define this area, a bounding box was constructed based on the minimum and maximum latitude and longitude values. A visual representation of the box is provided below.

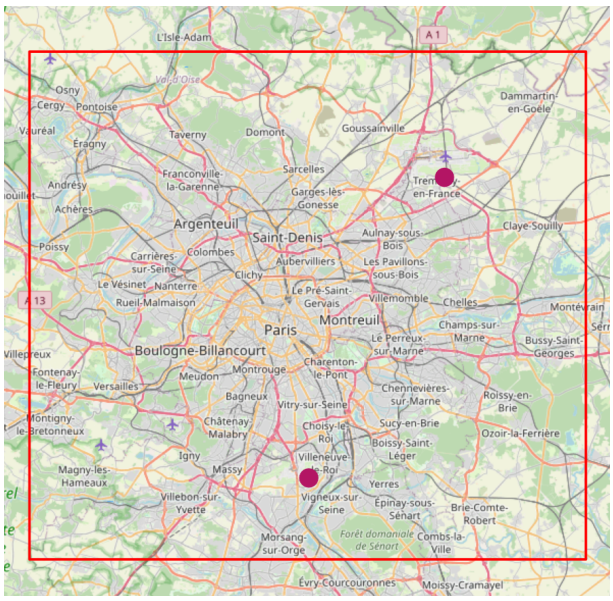

Figure 3: Selected Region

We then created a new dataframe that retained only the rows corresponding to flights whose position at timestep 0 (the start of measurement) fell within the specified range of latitude and longitude. For each aircraft, a list of unique segments was generated. Using this list, the initial dataframe was filtered to retain only the flights that matched the relevant segments.

To ensure comparability across all flights, we included only those whose measurements began between 0 and 100 meters altitude. A similar filtering method was employed: first, a dataframe was created containing only flights whose altitude at timestep 0 was below 100 meters. Then, using the segment indices, we compared and filtered the original dataset to isolate the flights that met the altitude criteria.

Finally, instead of saving the modified datasets as CSV files, we chose to store them as pickle files. This decision was based on the faster handling time associated with pickle files, as well as the fact that all team members are working with Python, making this format more convenient for our workflow.

The whole code for the data procession can be found in a seperate jupyter notebook file.
.

3 Q1: Velocity over Time during Climb Phase

The individual plots for each airplane by topic are provided in the appendix. For clarity and readability, only a comparative plot is shown in the main report.
For the first sub-research question, we want to look at the velocity change over time during the climb phase for each aircraft model (A319, A320, A321, and A332). It is interesting to analyze how the velocity changes over time during the climb phase and what kind of patterns are visible for this.

Since the data used for this research contained multiple flights/experiments for each aircraft model, the average and the standard deviation from the multiple flight experiments are used to visualize the values for the velocity over time. The average (mean) is displayed by the clearly visible lines and the standard deviation is indicated by the shadows around this average (visible lines). Here, the time step is from 0 until 1800 seconds.

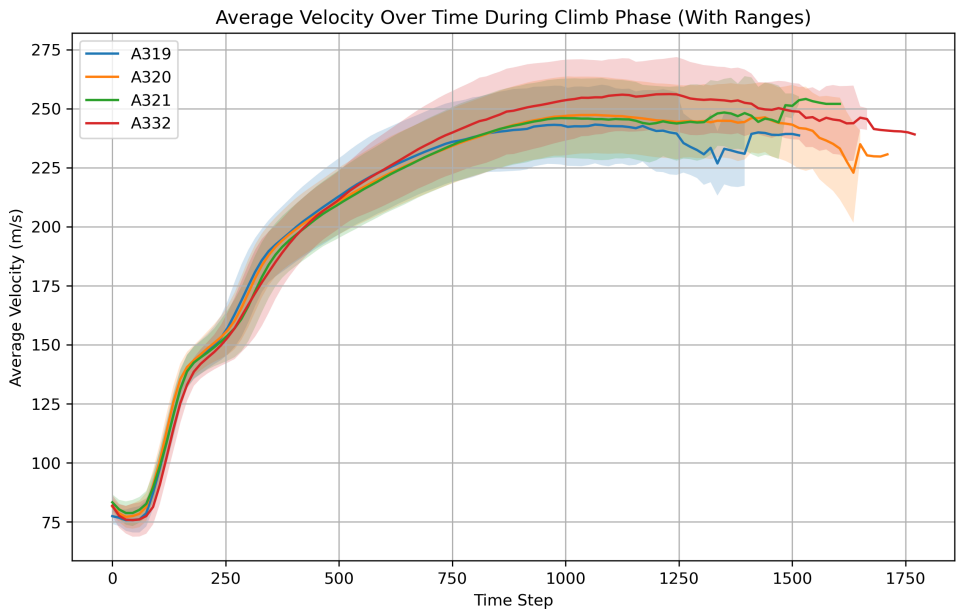

Figure 4: Velocity vs Time

From the figure above, it can be seen that for every aircraft model it has more or less the same pattern in the beginning (until timestep 500) and after that it starts to disperse for each aircraft model. In the beginning, the velocity of every model starts to increase linearly (until timestep 150), then it still increases but with a less steep slope (until timestep 250). After this timestep, the velocity again increases more steeply until it reaches more or less the velocity of 200 m/s and after that the velocity still increases slowly until it reaches the velocity of around 250 m/s and becomes steady at this point.

For the comparison between the aircraft models, if we look from the timestep 625 onwards or from the velocity 225 m/s onwards, it can be seen that the A332 model has the highest average velocity among the other models. At a certain timestep, it even reaches more than 250 m/s. There is certainly a gap of difference in average velocity between the A332 model and the other models. On the other hand, the A319 model has the lowest average velocity compared to other models, even though there is not much a different between the A319 model with the A320/A321 model. One possible reasoning for this is that A319 model is mostly used for short-term flights, hence it does not really need to have the "higher" velocity in order to cut the travel time. Meanwhile for A332 model, it is mostly used for long-haul flights, hence having the highest velocity in the engine might be beneficial to cut the travel time during the flight. Lastly, for the A320 and A321 models, they both have more or less the same average velocity throughout the time. If we look closely to the line plots of the A319 and A321 model (blue and green), it seems that there is a jump at the end of their time step. This could be due to the outliers in the data or the data for these particular timesteps is less compared to the previous timesteps.

In addition to that, it might also be interesting to see how the velocity behaves over the different altitude during the climb phase. The characteristics of the plot are the same as the previous one, however now the altitude is plotted on the x-axes.

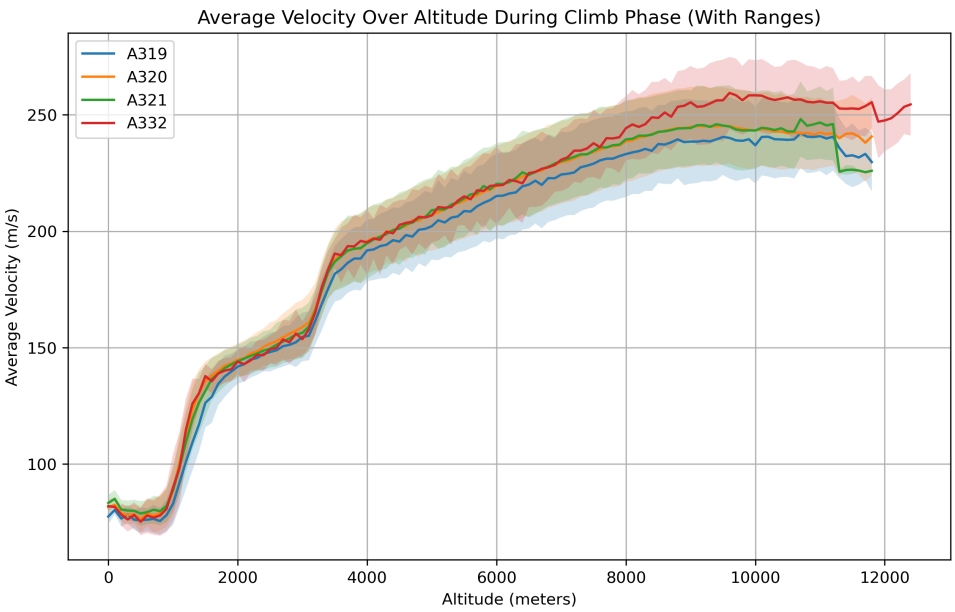

Figure 5: Velocity vs Altitude

The average velocity, in the graph presented above, behaves almost the same with the one presented against the timestep, however it looks a bit less subtle. The average velocity pattern behaves (exactly) the same as before, where in the beginning for every aircraft model, the average velocity starts to increase steeply until it reaches around 1800 meters of altitude. After that, it still increases however with a less steep slope until it reaches the altitude of a bit more than 3000 meters at the average velocity of 150 m/s. Then, it increases again more steeply until the average velocity almost reaches 200 m/s at the altitude of almost 4000 meters. After this altitude and onwards, the average velocity still increases slowly and it becomes steady around 250 m/s and at the altitude range of 10000 - 12000 meters.

For every aircraft models, the average velocity are the same more or less from altitude 0 meter until 3800 meters (almost 4000 meters). However, just right before the altitude of 4000 meters, the A319 model has the lowest average velocity compared to others. This holds until it reaches the altitude of 11000 meters. Meanwhile for the other three models (A320, A321, and A332), the average velocity are the same until it reaches 8000 meters of altitude where the A332 model has a larger increase in average velocity which makes it having the largest average velocity from this altitude and onwards. It even exceeds the average velocity of 250 m/s from the altitude range of 9000 meters to 12000 meters. Lastly, at the altitude around 11000 meters, the average velocity is roundly the same for the A319, A320, and A321 models, in which it reaches almost 250 m/s.

4 Q2: Altitude Change over Time during Climb Phase

For the second sub-research question, it would also be interesting to analyze how the altitude of the different aircraft models (A319, A320, A321, and A332) behaves over time during their climb phase. How high these different aircraft models reaches a certain altitude over/at a specific time step will be plotted.

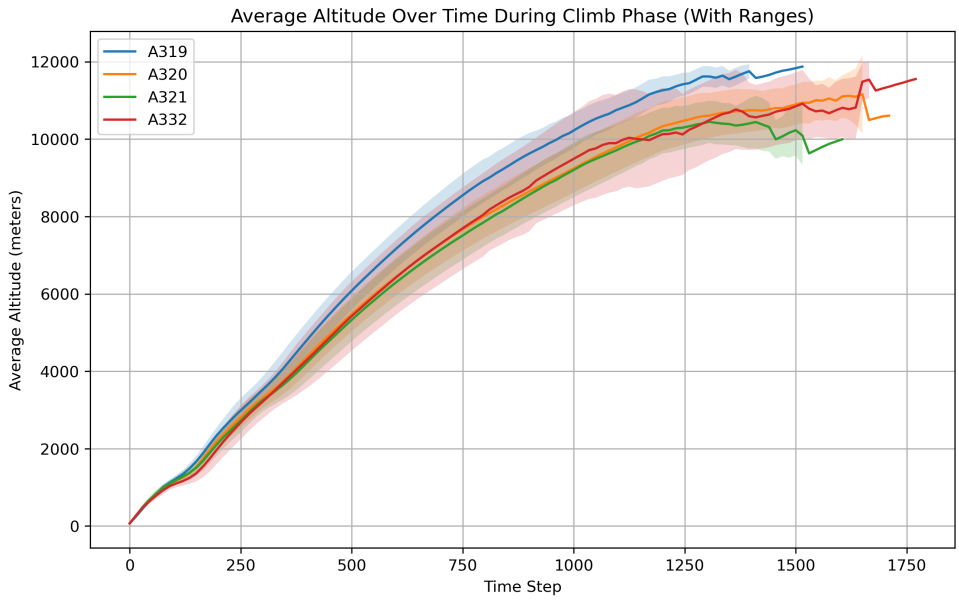

Figure 6: Altitude vs Time

The average altitude over the time plot shows that the average altitude for every aircraft model increases smoothly throughout the time. The dispersion in the increase of the average altitude can already be seen from the timestep around 300 where the A319 model's average altitude starts to increase way more higher and has a bit more steeper slope compared to other models. Hence, from that timestep onwards, the A319 model has already a higher altitude compared to others by looking at that particular timestep. In the end, it reaches 12000 meters of altitude in average way more faster/earlier compared to other models, at the timestep of 1500 seconds. Meanwhile for other models (A320, A321, and A332), the increase in average altitude is more or less the same throughout the time. Unless if we look around the timestep 1000, here the average altitude for the A332 model is higher compared to the A320 and A321 model. However, after this period of timestep, it becomes similar again in the average altitude. Reaching the end of the timestep (around 1500 seconds), it seems that the A321 model has a decrease in average altitude for whatever reason. All in all, for these three aircraft models (A320, A321, and A332), they have a range of 10000 - 11000 meters for its average altitude at this particular timestep of 1500 seconds or 25 minutes.

One possible reason why the A319 model has the highest altitude among the other models at a particular timestep is that it could be that the A319 model should already be as high as possile during the climb phase since it is only doing a short period of flight. Hence, it has to be as high as possible in altitude in order to avoid traffic, which occurs in the air, as soon as possible.

The animation visualizing the trajectory of each aircraft's climb model based on altitude over time highlights the differences in each aircraft's climb can be found in a seperate jupyter notebook file. It will be discussed further in the subsequent research question.

5 Q3: Climb Rate Change over Time

This research question aims to investigate the changes in climb rate over time during the climb phase of selected Airbus aircrafts. In this analysis, various aspects of the climb rate are analysed and the external influencing factors (wind, etc.) are not taken into account. The aim is to achieve a tendency in comparison with the respective aircraft types.

One possible reason for these deviations may be technical differences in performance, such as different engine power specifications, aerodynamics and overall weight. Tech 2024

5.1 Calculating the Climb Rate

The climb rate is a measurement of how quickly an aircraft can increase its altitude. It is usually expressed in feet per minute (fpm) or meters per second (m/s). This parameter is crucial in aviation, affecting the efficiency, safety, and performance of flight operations. Tech 2024

The climb rate can be calculated using the formula:

$$\text{Climb Rate} = \frac{\Delta\text{Altitude}}{\Delta\text{Time}}$$

Where:

- ΔAltitude is the change in altitude.
- ΔTime is the time it takes for that change.

5.2 Analysis of the Climb Rate

The following diagrams compare the climb rates and their deviations among four different aircraft models, providing deeper insight into the operational stability and consistency of each model.

The climb rate diagram represents the typical performance of an aircraft under standard conditions, essential for understanding its capabilities in average scenarios. Deviations from the average rate indicate how individual flights differ from the norm. Significant discrepancies can result from varying operating conditions such as weather, loading, or maintenance status. Tech 2024

Airbus A319

The A319 shows an initial high climb rate. The average rate of climb decreases relatively smoothly after the initial peak. There is a high degree of variability in individual climb rate from flight to flight, particularly early in the climb. The data points spread widely around the average, indicating different performance under different conditions or different operating modes.

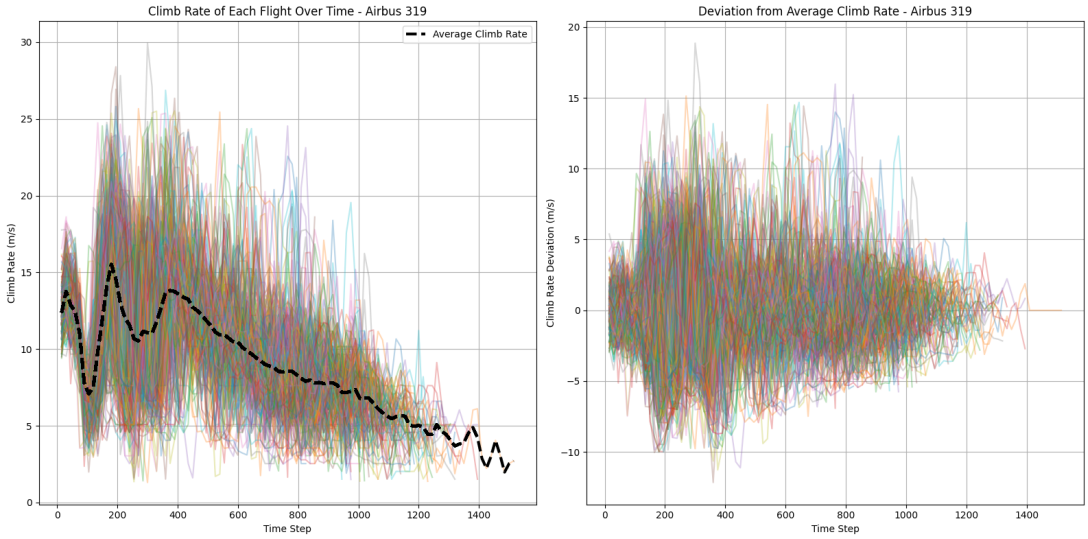

Figure 7: A319: Climb Rate vs. Time

Airbus A320

Similar to the A319, the A320 starts with a high climb rate. The climb rate average looks to be slightly slower than the A319. Considerable variability is also visible here, but somewhat less than with the A319. The climb rate appears to be slightly more consistent, which could indicate more stable performance or better operating conditions.

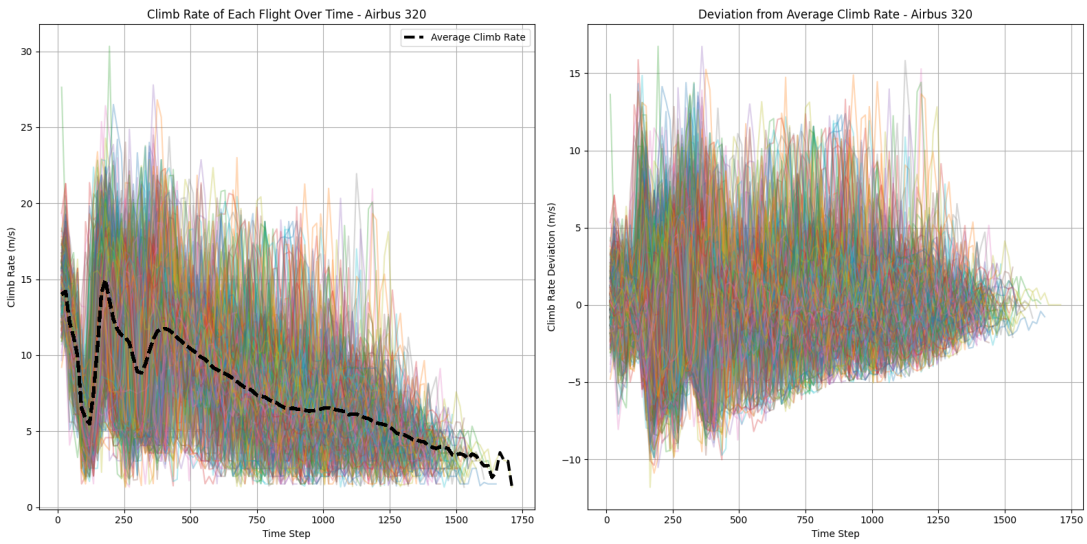

Figure 8: A320: Climb Rate vs. Time

Airbus A321

The deviations at the A321 from the average climb rate are especially notable in the middle phase of the climb.

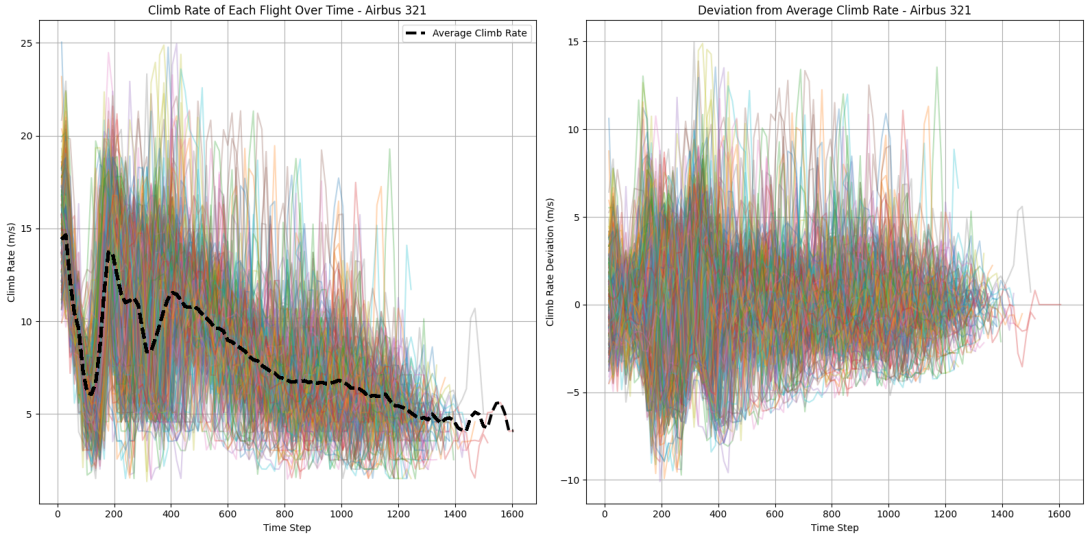

Figure 9: A321: Climb Rate vs. Time

Airbus A332

The course of the average climb rate of the A332 shows a steady and even decline. The spread of the climb rates around the average is overall less variable than in the smaller models. This could indicate that the A332 performs more consistently under a wider range of operating conditions.

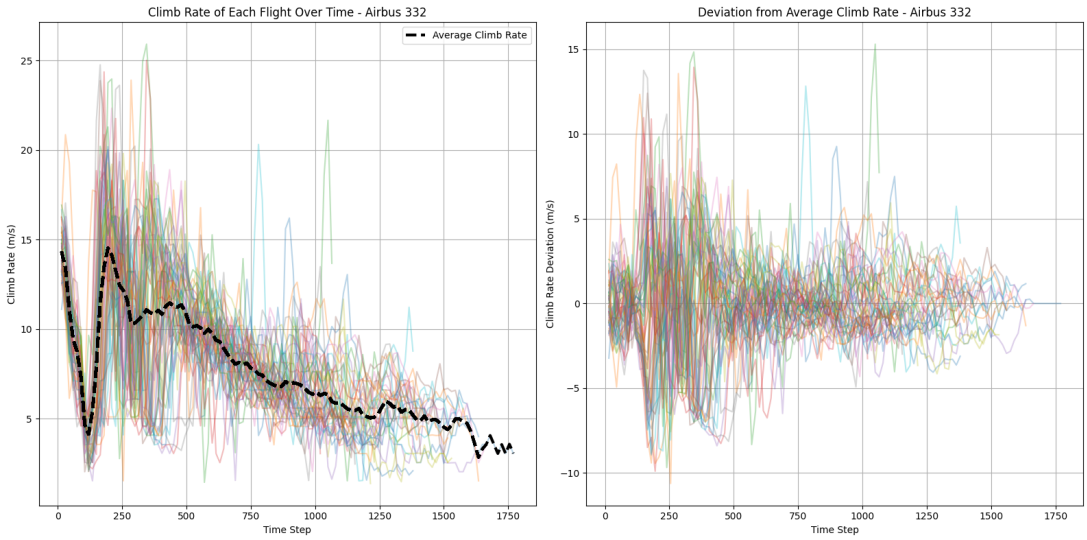

Figure 10: A332: Climb Rate vs. Time

Comparison of the Four Aircrafts

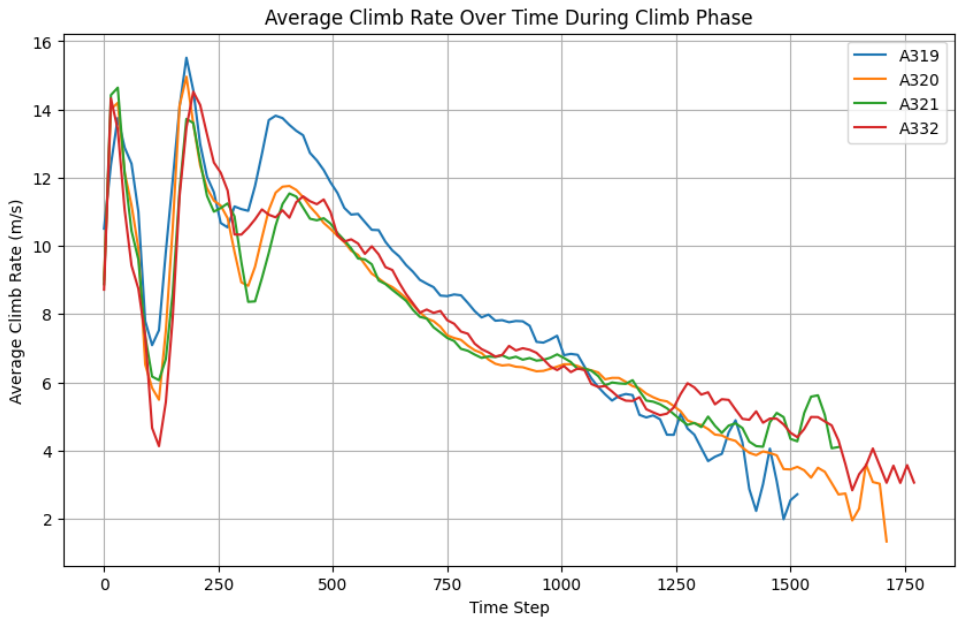

Figure 11: Climb Rate vs. Time with Reference to Optimal Climb Rate Range

Each aircraft model has its own optimal climb rate specified by the manufacturer. However, the actual climb performance of each model on every flight depends on various factors, primarily the objective to minimize costs (cost efficiency) during the flight, including the climb phase, while also complying with regulations and restrictions set by Air Traffic Control (ATC). The figure below shows the climb rate for each aircraft model with the proposed optimal climb rate range indicated.

5.2.1 Conclusion

The following findings can be derived from the diagram:

- **Initial Peaks and Fluctuations**
  All models show an initial peak in climb rate followed by significant fluctuation before reaching a more stable climb rate. This is a common model in aviation, called step climbing. This is done to improve fuel economy by moving into thinner air as an aircraft becomes lighter and becomes capable of flying in the thinner air at a higher altitude.

- **Decrease in Rate of Climb**
  After the initial climb and subsequent fluctuations, the rate of climb gradually decreases in all models. This is typical as airplanes have a decreasing climb rate with increasing altitude and approaching the target altitude. Marchman 2024

- **Differences Between the Models**
  The A320 and A321 show similar behavior with a rapid recovery after the initial fall and a subsequent gradual decrease. The A332 shows a slightly more stable and consistent climb rate after the initial peak, while the A319 tends to have a lower climb rate and shows the greatest fluctuations over time. Tech 2024

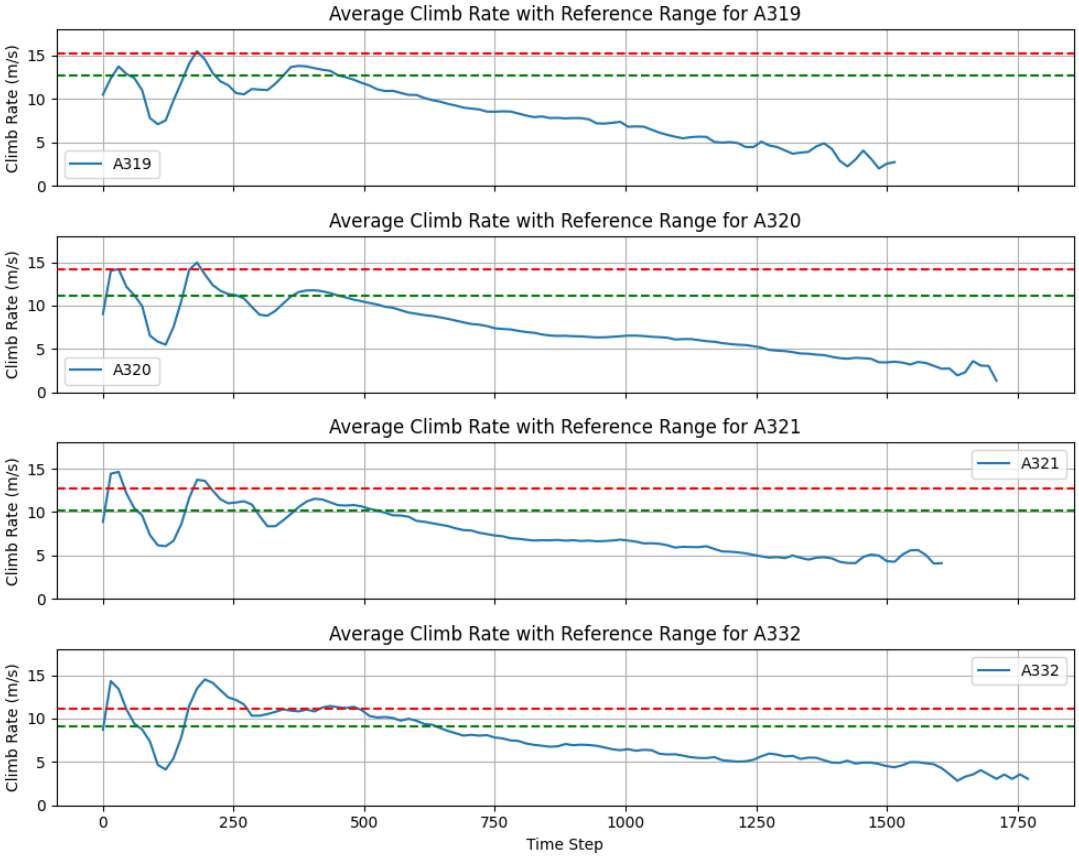

Figure 12: Climb Rate vs. Time with Reference to Optimal Climb Rate Range

5.3 Comparison of Q3 to the Climb Rate Change over Barometric Altitude

To verify the third research question and compare the results, the average climb rate (in meters per second) versus barometric altitude (in meters) for the different Airbus models during the climb phase was analyzed. Compared to the graph showing climb rate over time steps, this barometric altitude plot provides direct insights into the performance of the aircraft as a function of the altitude reached.

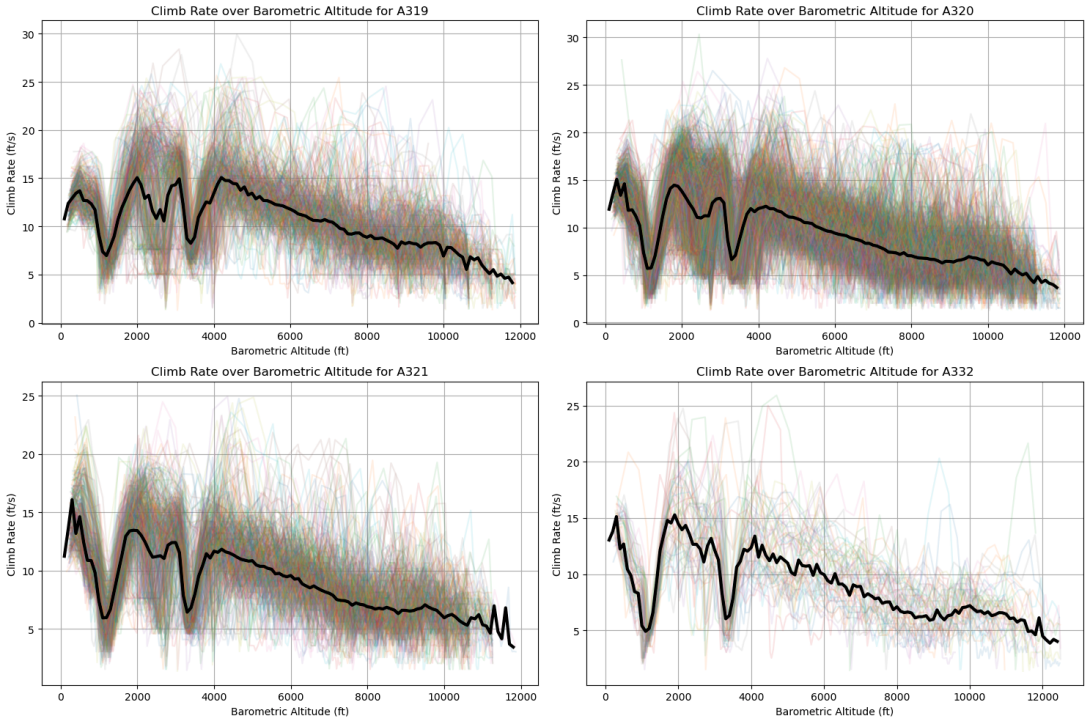

Figure 13: Climb Rate over Barometric Altitude for each Aircraft

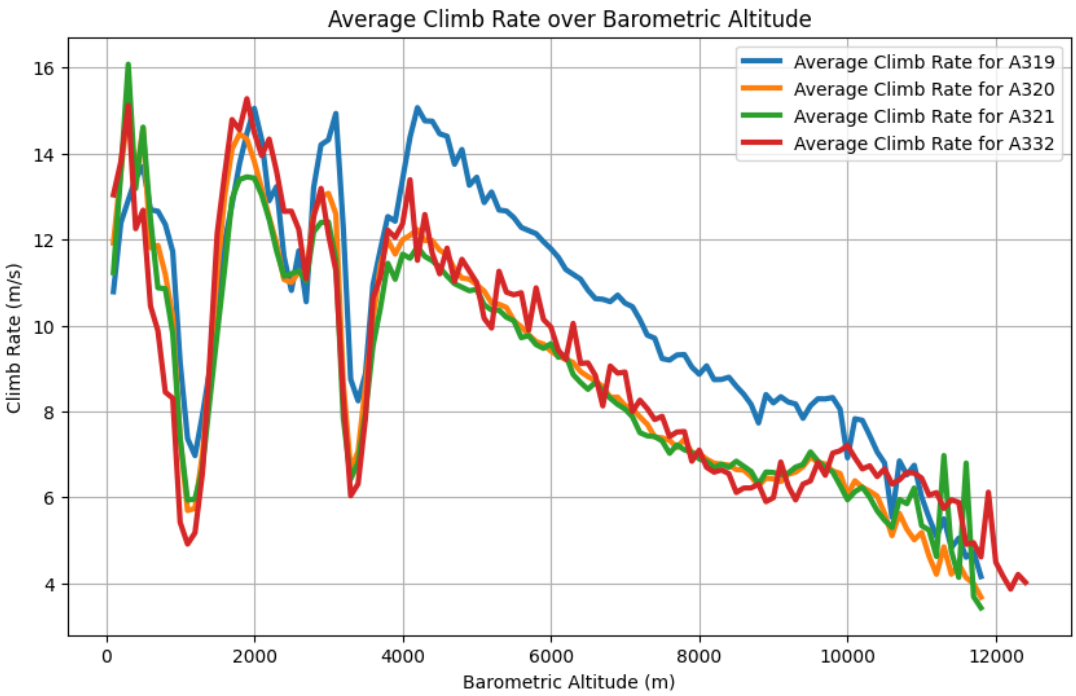

Figure 14: Comparison of Climb Rate over Barometric Altitude

The similarities to RQ 3 can be seen in the following:

- **Decreasing Climb Rate**
  Both graphs exhibit a general trend of decreasing climb rate over time and altitude. This decline is attributed to physical limitations such as decreasing air density and engine power at higher altitudes, as well as the approach to the target altitude. Leishman 2023

- **Initial Fluctuations**
  Both graphs show strong fluctuations in the initial phases of the climb rate.

- **Model-Specific Patterns**
  Both graphs indicate that different Airbus models have distinct profiles concerning their climb rates, with each model exhibiting specific characteristics consistent across both graphs:

  - The A320 and A321 models demonstrate similar behavior, with the A321 performing slightly better at higher altitudes.
  - The A319 shows greater fluctuations and an overall lower climb rate.
  - The A330-200 (A332) performs particularly well at medium to high altitudes.

  These performance variations among models can be attributed to differences in engine configurations, aerodynamics, and weight distributions.

The differences to RQ 3 are as follows:

- **Interpretability**
  The climb rate versus altitude chart provides more direct insights into the aircraft's flight dynamic characteristics and performance. It shows at which altitude levels the climb rate is maximized or minimized. For example, the graph shows peaks and troughs in climb rate at certain altitudes, which could indicate optimal or sub-optimal operating conditions.

- **Use for Practical Applications**
  The graph over time might be better for time-related optimizations (e.g., flight duration), while the graph over altitude is more important for performance-related adjustments in flight operations. Both graphs complement each other, confirming that RQ 3 used the correct data and applied the model correctly.

6 Q4: Factors Contributing to Deviations from the Defined Optimal Climb Rate

For the last sub-research question, we want to look at the factors contributing to the optimal climb rate for each aircraft model (A319, A320, A321, and A332). It is interesting to analyze what and how are the various factors correlate to climb behavior over time during the climb phase and what kind of patterns are visible for this.
Climbing is one of the phase of flight that can be identified directly after Take-Off, which is started by the initial climb phase. Initial climb started from the end of the take-off run sub-phase to the first prescribed power reduction, or until reaching first initial assigned altitude target above runway elevation, whichever comes first. Following that, the aircraft undergoes En-Route phase (ENR), starting from completion of Initial Climb through cruise altitude or initial assigned cruise altitude.

6.1 Correlation Analysis

The figure below displays the Pearson correlation coefficient values, which range from -1 to 1. A value of 1 indicates a perfect positive linear relationship, -1 indicates a perfect negative linear relationship, and 0 indicates no linear relationship.
Based on these values, specific factors are selected for further analysis:

Due to missing information regarding the correction calculation for **vetraratecorr**, this value is excluded from consideration.
Timestep and **distance_from_dep**: As the distance from the airport increases, the climb rate tends to decrease. This relationship also explains the correlation observed with **lat**, as it reflects the direction in which aircraft depart.
Baroaltitude has been addressed in previous sections.
For the **fromICAO** parameter, due to inconsistencies and missing data, correlation calculations could not be performed for the A321 and A332 models. However, for A319 and A320, the results indicate no significant correlation.

This leaves **velocity**, **tas**, and **temp** for further analysis. Given the characteristics of these parameters, **tas** is chosen over **velocity** for detailed examination.

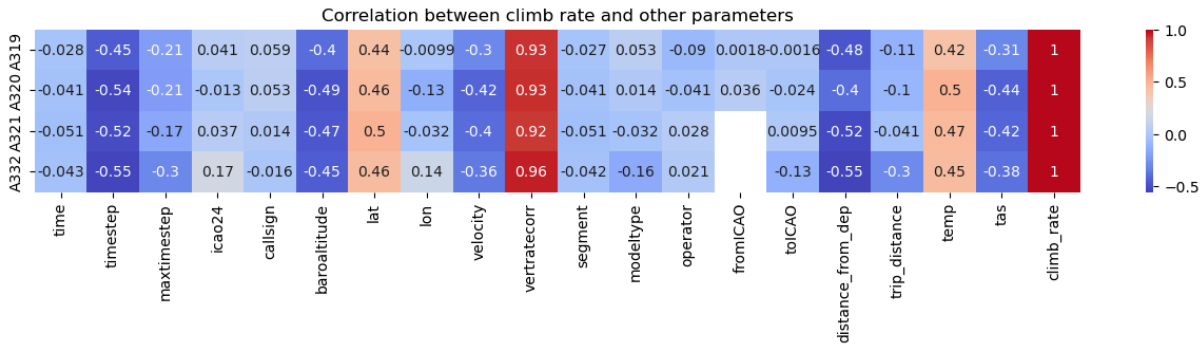

Figure 15: Correlation Between Climb Rate and Other Parameters

6.2 True Air Speed

For the True Airspeed (TAS) parameter, the figures below show a slight downward trend in TAS when observed in relation to climb rate. This suggests that a lower TAS generally corresponds to a steeper climb, while a higher TAS correlates with a shallower climb. However, there is no clear indication of a direct correlation. The nature of climb rate, as discussed in RQ3, appears to be model-specific, potentially influenced by efficiency optimization or ATC adjustments due to airspace restrictions. The relationship between climb rate and TAS is also primarily model-specific during the climb phase. The 'swirl' profiles in the figures below represent each segment's pattern, with color indicating the density of these repeating

patterns across segments.

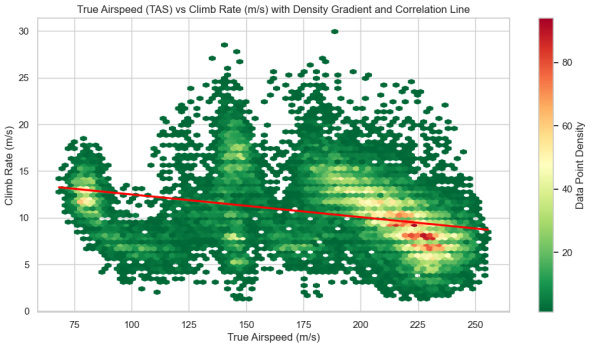

Figure 16: A319: Climb Rate vs. True Airspeed

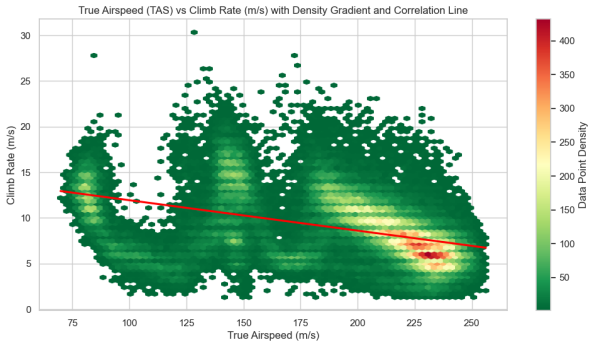

Figure 17: A320: Climb Rate vs. True Airspeed

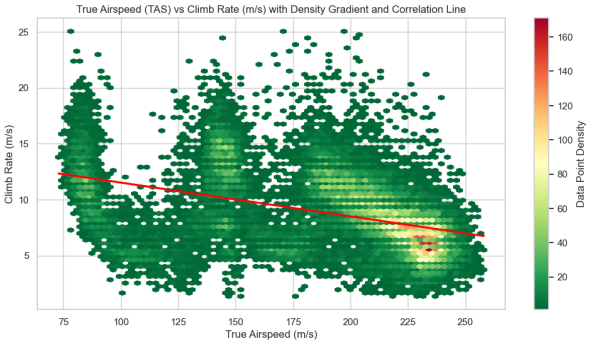

Figure 18: A321: Climb Rate vs. True Airspeed

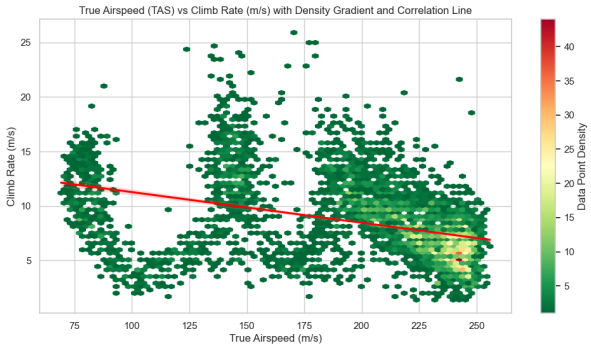

Figure 19: A330-200: Climb Rate vs. True Airspeed

A more appropriate representation of True Airspeed (TAS) should be based on its correlation with altitude. According to Peeters (2013), when an airline considers the cost of time as being the most important, the descent should be done in the smallest amount of time possible. Each aircraft has an ideal descent and climb profile to minimize costs, which can be illustrated by plotting altitude over TAS, showing the ideal trajectory for these profiles as depicted in the figure below. However, further analysis of cost efficiency is beyond our scope, and additional data, such as thrust levels and fuel consumption, would be necessary for such analysis.

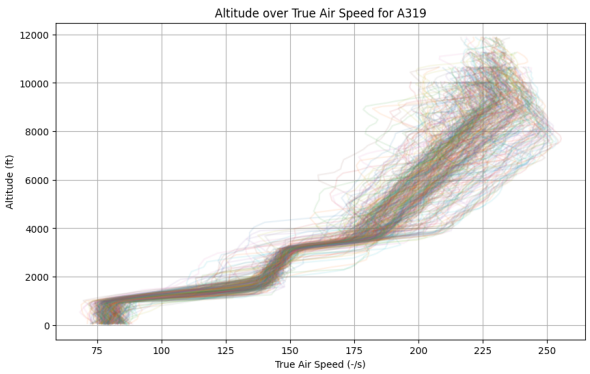

Figure 20: A319: Altitude vs. True Airspeed

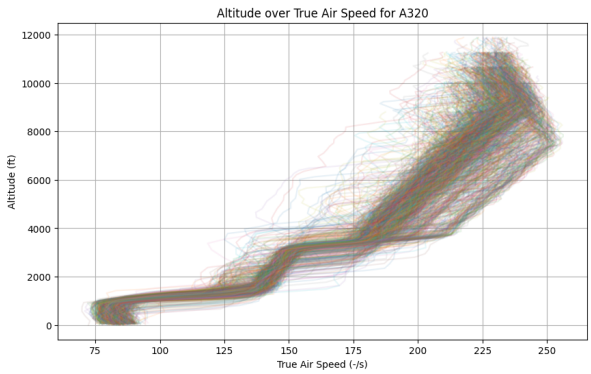

Figure 21: A320: Altitude vs. True Airspeed

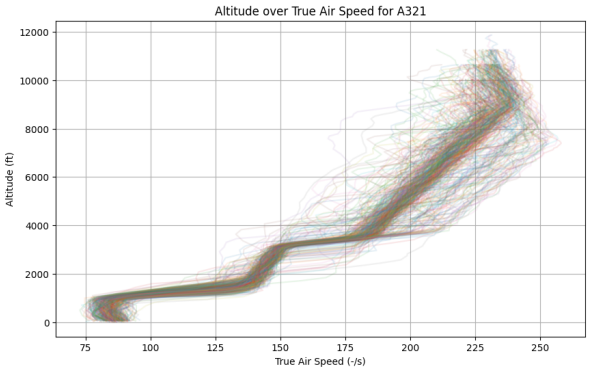

Figure 22: A321: Altitude vs. True Airspeed

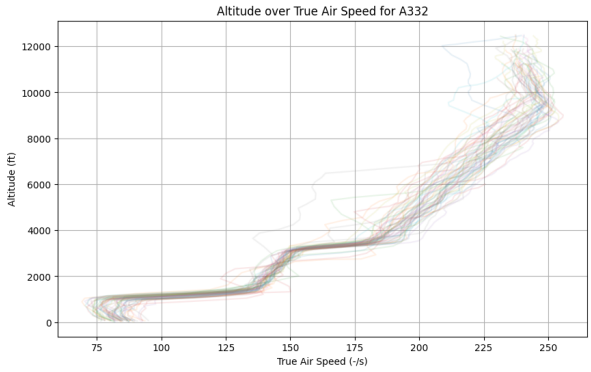

Figure 23: A330-200: Altitude vs. True Airspeed

6.3 Temperature

The aerodynamic upforce generated by the airfoil depends on the temperature as it correlates directly with air density Toolbox 2004. The temperature shows a slight upward trend in relation to climb rate. This suggests that lower temperatures generally correspond to a shallower climb, typically occurring as the aircraft approaches the end of its climb phase, nearing the assigned altitude (such as cruising altitude). In contrast, higher temperatures, usually experienced at lower altitudes, correspond to a steeper climb as the aircraft is in the initial stage of its climb phase, aiming to achieve optimal climb speed. However, similar to the True Airspeed parameter, direct correlation also depends on the nature of the climb rate, as previously stated, it is mainly influenced by the efficiency optimization of each specific aircraft model and scenario.

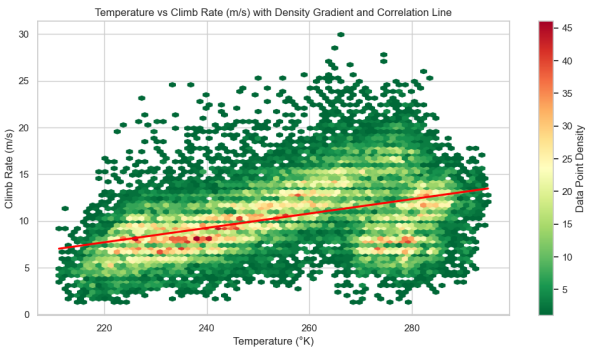

Figure 24: A319: Climb Rate vs. Temperature

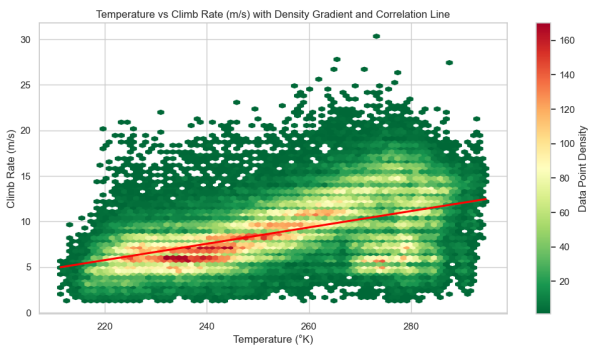

Figure 25: A320: Climb Rate vs. Temperature

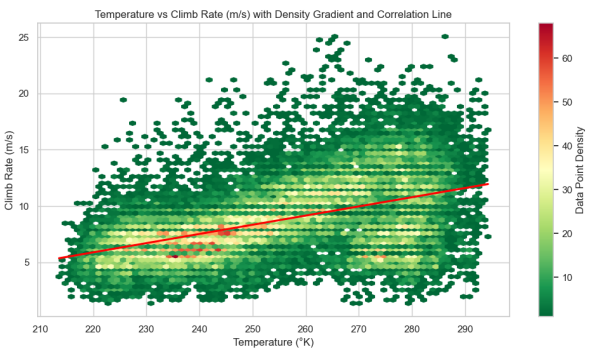

Figure 26: A321: Climb Rate vs. Temperature

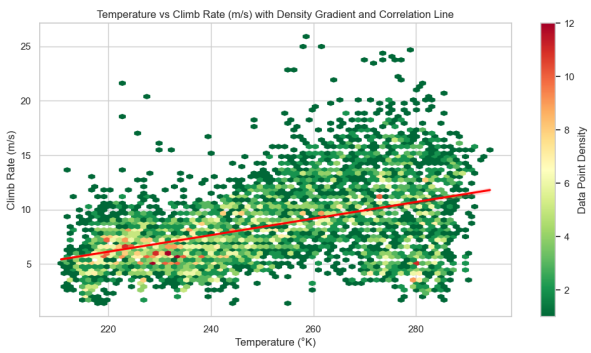

Figure 27: A330-200: Climb Rate vs. Temperature

7 Conclusion

In conclusion, the analysis of velocity changes during the climb phase reveals that different aircraft models exhibit distinct speed behaviors. While all models (A319, A320, A321, and A332) initially show similar patterns of increasing velocity, the A332 eventually attains the highest average speeds, likely because it operates on long-haul flights where higher velocities help reduce travel time. The A319 maintains the lowest average velocities, which may be due to its use on shorter routes where extreme speeds are less necessary. The A320 and A321 have similar velocity profiles that fall between those of the A319 and A332.
The analysis of altitude over time during the climb phase reveals that different aircraft models exhibit distinct ascent behaviors. The A319 climbs more rapidly than the A320, A321, and A332, likely because it operates on shorter flights and needs to reach cruising altitude quickly to avoid air traffic. The other models show similar climb patterns with minor variations, which may be attributed to their roles in longer-haul flights.
The analysis of climb rate changes during the climb phase shows that different Airbus aircraft models exhibit distinct ascent behaviors. All models experience an initial peak in climb rate followed by fluctuations and a gradual decrease as they ascend. The A320 and A321 display similar patterns with rapid recovery after initial fluctuations, while the A332 maintains a more stable and consistent climb rate, particularly at medium to high altitudes. In contrast, the A319 shows greater fluctuations and a generally lower climb rate, possibly due to technical differences such as engine power, aerodynamics, and weight. Comparing climb rate over time and altitude confirms these findings and demonstrates that different models have unique performance profiles during ascent.
The analysis of factors influencing the optimal climb rate for Airbus models A319, A320, A321, and A332 indicates that True Airspeed (TAS) and temperature have nuanced effects on climb behavior. Due to steeper climb rates in the beginning of each climb, lower TAS tend to correspond with steeper climbs, while higher TAS align with shallower ascents; however, this relationship is not strongly direct and varies between aircraft models due to efficiency optimizations and air traffic control constraints. Similarly, higher temperatures at lower altitudes are associated with steeper climbs, whereas lower temperatures at higher altitudes correlate with shallower climbs as aircraft approach cruising altitude. These findings suggest that while TAS and temperature do impact climb rates, their influence is intertwined with model-specific characteristics and operational scenarios, highlighting the complexity of optimizing climb performance.

Overall, these analyses highlight the complexity of climb performance among different aircraft models, influenced by a combination of design features, operational practices, and influencing external factors. Recognizing these distinctions is essential for optimizing flight operations and enhancing efficiency across various flight profiles. Future research could further explore these relationships by incorporating additional variables such as aircraft weight and wind conditions.

8 Contribution Statement

The following table provides an overview of which team members worked on each task. However, in our group meetings many tasks were partially collaborated on. Therefore, the table serves as a general representation only.

Content	**Code**	**Text**
1	/	Stefan, Paul
2.1	Paul	Paul
2.2	Kai	Kai
3	Bryan, Stefan	Bryan
4	Bryan, Stefan, Mega	Bryan
5.1	/	Mega
5.2	Stefan	Stefan
5.3	Kai	Stefan
6	/	Mega
6.1	Kai	Kai
6.2	Paul, Mega	Mega
6.3	Paul	Mega
7	/	Paul, Kai
Formatting	/	Stefan, Kai

Table 1: Contribution Statement

List of Figures

2 Overview of Aircraft types . . . 2
3 Selected Region . . . 4
4 Velocity vs Time . . . 5
5 Velocity vs Altitude . . . 6
6 Altitude vs Time . . . 7
7 A319: Climb Rate vs. Time . . . 9
8 A320: Climb Rate vs. Time . . . 9
9 A321: Climb Rate vs. Time . . . 10
10 A332: Climb Rate vs. Time . . . 10
11 Climb Rate vs. Time with Reference to Optimal Climb Rate Range . . . 11
12 Climb Rate vs. Time with Reference to Optimal Climb Rate Range . . . 12
13 Climb Rate over Barometric Altitude for each Aircraft . . . 13
14 Comparison of Climb Rate over Barometric Altitude . . . 13
15 Correlation Between Climb Rate and Other Parameters . . . 15
16 A319: Climb Rate vs. True Airspeed . . . 16
17 A320: Climb Rate vs. True Airspeed . . . 16
18 A321: Climb Rate vs. True Airspeed . . . 16
19 A330-200: Climb Rate vs. True Airspeed . . . 16
20 A319: Altitude vs. True Airspeed . . . 16
21 A320: Altitude vs. True Airspeed . . . 16
22 A321: Altitude vs. True Airspeed . . . 17
23 A330-200: Altitude vs. True Airspeed . . . 17
24 A319: Climb Rate vs. Temperature . . . 17
25 A320: Climb Rate vs. Temperature . . . 17
26 A321: Climb Rate vs. Temperature . . . 17
27 A330-200: Climb Rate vs. Temperature . . . 17
28 Velocity vs Time for A319 . . . 21
29 Velocity vs Time for A320 . . . 21
30 Velocity vs Time for A321 . . . 21
31 Velocity vs Time for A332 . . . 21
32 Velocity vs Altitude for A319 . . . 21
33 Velocity vs Altitude for A320 . . . 21
34 Velocity vs Altitude for A321 . . . 22
35 Velocity vs Altitude for A332 . . . 22
36 Altitude vs Time for A319 . . . 22
37 Altitude vs Time for A320 . . . 22
38 Altitude vs Time for A321 . . . 22
39 Altitude vs Time for A332 . . . 22

Literature

OpenSky-Network (2024). *Climbing Aircraft Dataset.* URL: https://opensky-network.org/data/datasets#d7.

Tech, Aeroplane (2024). *Understanding the Rate of Climb: A Key Factor in Aviation.* URL: https://aeroplanetech.com/rate-of-climb/.

Marchman, James F. (2024). *Altitude Change: Climb and Guide.* URL: https://eng.libretexts.org/Bookshelves/Aerospace_Engineering/Aerodynamics_and_Aircraft_Performance_3e_%28Marchman%29/05%3A_Altitude_Change-_Climb_and_Guide.

Leishman, J. Gordon (2023). *Introduction to Aerospace Flight Vehicles.* URL: https://eaglepubs.erau.edu/introductiontoaerospaceflightvehicles/chapter/climbing-ceiling-gliding/.

Peeters, Sam (2013). *Adaptation of continuous descent and climb operational techniques at Brussels Airport aiming at cost efficiency.* Accessed: 20-10-2024. URL: https://ansperformance.eu/library/sam-thesis.pdf.

Toolbox, The Engineering (2004). *Air - Density vs. Pressure and Temperature — engineeringtoolbox.com.* https://www.engineeringtoolbox.com/air-temperature-pressure-density-d_771.html. [Accessed 08-11-2024].

A Appendix

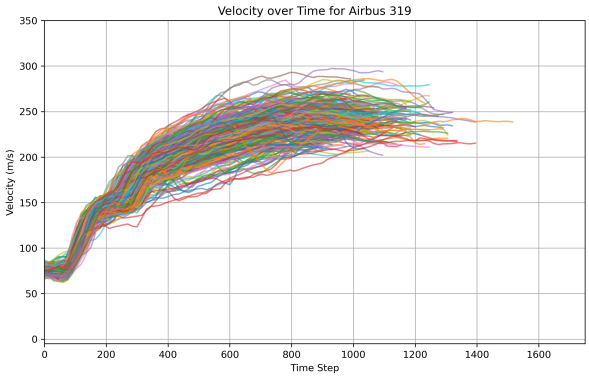

Figure 28: Velocity vs Time for A319

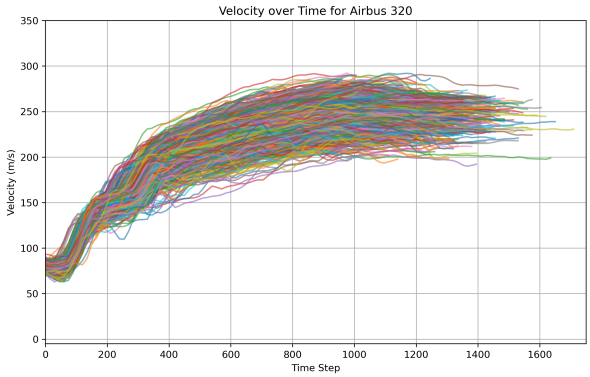

Figure 29: Velocity vs Time for A320

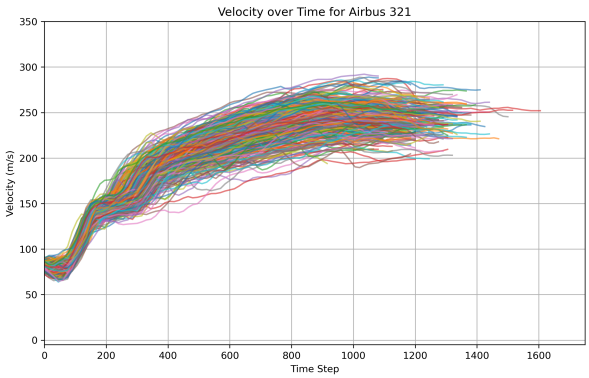

Figure 30: Velocity vs Time for A321

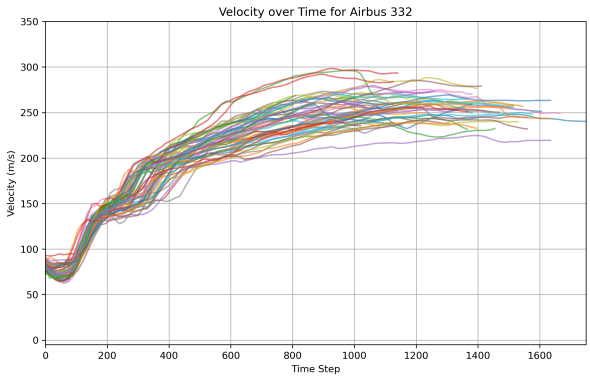

Figure 31: Velocity vs Time for A332

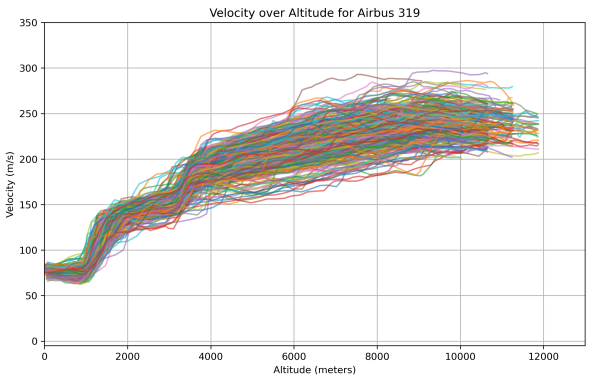

Figure 32: Velocity vs Altitude for A319

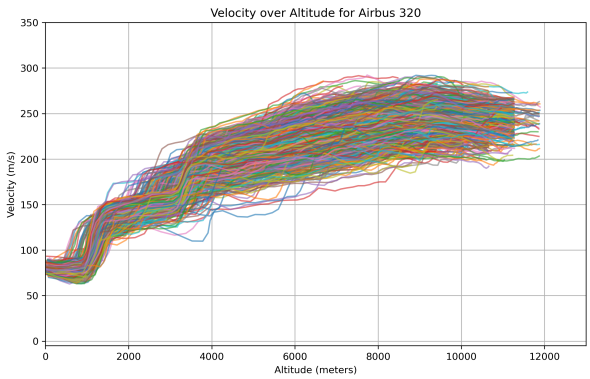

Figure 33: Velocity vs Altitude for A320

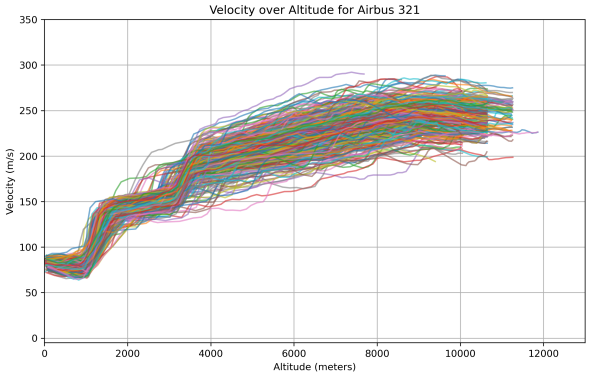

Figure 34: Velocity vs Altitude for A321

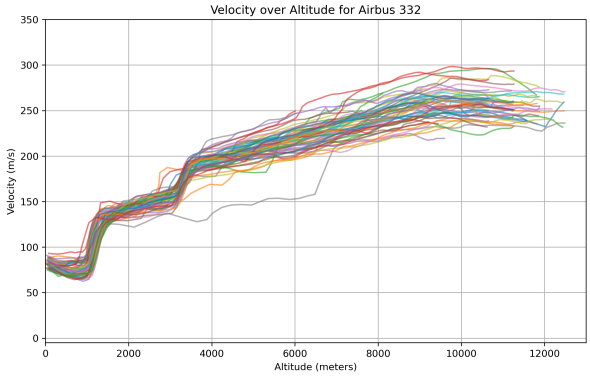

Figure 35: Velocity vs Altitude for A332

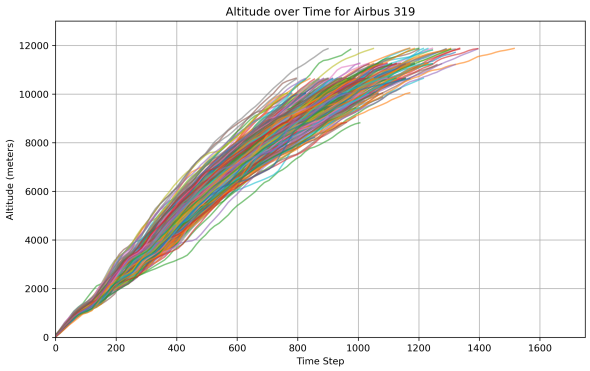

Figure 36: Altitude vs Time for A319

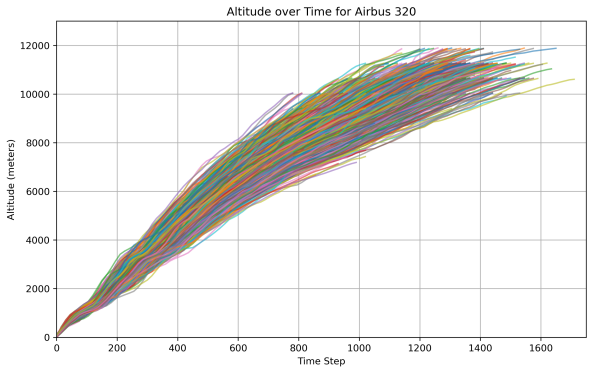

Figure 37: Altitude vs Time for A320

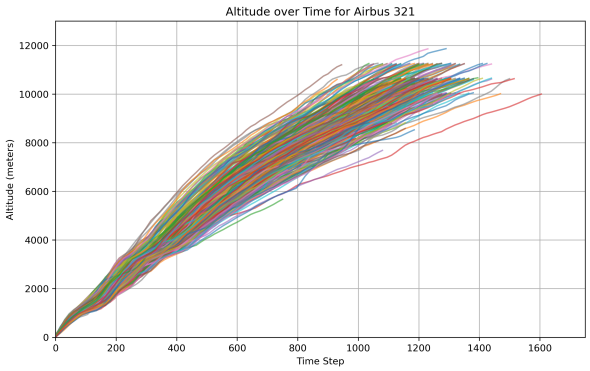

Figure 38: Altitude vs Time for A321

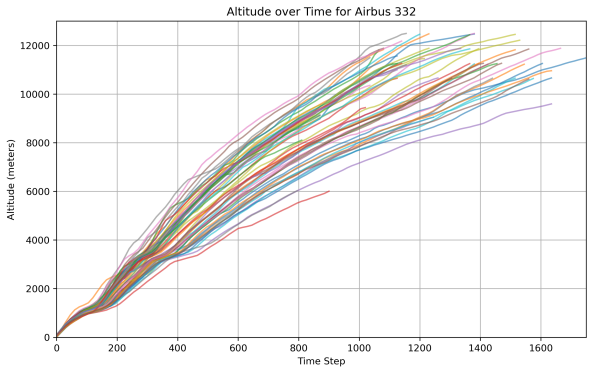

Figure 39: Altitude vs Time for A332