An Improved Understanding of En-route Wake Vortex Encounters

Mike HOOGSTRATEN [a,1], Hendrikus VISSER [a], Dennis HART [b], Vincent TREVÉ [b] and Frederic ROOSELEER [b]

[a] *Delft University of Technology, Delft, The Netherlands*
[b] *EUROCONTROL HQ, Brussels, Belgium*

Abstract. Wake turbulence can be experienced by aircraft when encountering the wake vortex of another aircraft. Wake turbulence research in the past has focussed mainly on the departure and approach phase of flight, yet wake turbulence can affect every flight phase. From 2009 to 2012, 26 wake turbulence incidents were reported during the en-route flight phase in upper European airspace. The aim of this study is to improve understanding of the risk posed by en-route wake vortex encounters in upper airspace. The risk is analysed by creating a simulation which uses recorded historical surveillance data and recreates the wake vortex trajectories for each aircraft based on a wake vortex model. The simulation is able to reproduce 75% of the 12 reports for which meteorological and surveillance data was available. The simulation is used to determine the probability of encountering a wake vortex in upper airspace. The simulation shows that severe wake vortex encounters could be expected approximately once every 38 days. Three aspects have been identified which contribute to the risk of encountering a wake vortex during the en-route phase of flight. These three aspects include the characteristics of the exposed or generating aircraft, the encounter geometry and the tropopause height. The combined time evolution of these three aspects suggests that the en-route wake vortex encounter risk may increase in the future. Finally, mitigation measures are proposed which could be implemented on a short and long term basis and which could reduce the severity of wake vortex encounters or even prevent them occurring.

Keywords. En-route, upper airspace, wake turbulence, wake vortex, simulation, tropopause

Introduction

Wake vortex is a complex and dynamic phenomenon which is directly linked to the lift-generating abilities of aircraft. Wake vortices generated by aircraft in en-route conditions have been reported to last up to three minutes. Aircraft which encounter a wake vortex will experience wake-induced turbulence. This turbulence is often encountered without warning and has been reported to induce roll angles of up to 45 degrees. Since it is often encountered without warning, pilots may not have enough time to notify cabin crew and passengers in advance. Therefore, cabin crew and passengers who are neither seated nor wearing their seat belts have a high risk of being injured.

[1] Corresponding Author: Graduate Master Aerospace Engineering, Linnaeusweg 34, 5915 HL Venlo, The Netherlands; E-mail: mmjt.hoogstraten@gmail.com

The need for a better understanding of en-route wake vortex related issues is highlighted by the evolution of the air traffic mix. In recent years “Very Light Jet” and “Super Heavy” aircraft have been introduced. The operational flight envelopes of these aircraft allow them to operate at similar cruise altitudes. A previous study analysed the hazard of en-route wake vortex encounters in 1999. This study was conducted to assess the possible impact of Reduced Vertical Separation Minimum (RVSM) on the risk of encountering a wake vortex en-route [14]. This study emphasised the need to monitor and analyse wake turbulence reports which occur above 5000 feet after the introduction of RVSM. Between July 2009 and July 2012, 73 wake turbulence incidents were reported to have occurred above 5000 feet. In total, 26 of these incidents occurred above FL285. The aim of this study is to analyse the risk of wake vortex encounters in upper airspace. In this study, flights are considered to be in upper airspace when flying above FL285, the boundary set in Europe [10].

Three objectives have been defined to analyse the risk of wake turbulence in upper airspace. The first objective is to determine the probability of an en-route wake vortex encounter occurring above FL285. The second objective is to identify the main factors which contribute to the risk and to assess their evolution over time. The third objective is to assess what safety measures might mitigate the risk in the current Air Traffic Management (ATM) system. Mitigation measures which may reduce the risk are proposed on the basis of current and potential future technologies.

1. Methodology

The study was conducted in four steps. Firstly, the probability of a wake vortex encounter occurring in European airspace was estimated using a simulation framework, designed in the course of the study, based on a wake vortex model proposed by De Visscher [11]. The simulation uses numerical meteorological data in combination with historical surveillance data and the wake vortex model to produce the wake vortex trajectories of aircraft. An initial study at EUROCONTROL has already shown the applicability of existing wake vortex models, in combination with numerical meteorological forecast data, to en-route aircraft [1]. Secondly, this simulation was applied to 24 days of surveillance data, including over 400,000 flights, in order to estimate the probability of wake vortex encounters occurring en-route. Thirdly, factors were identified which influence the risk of encountering wake vortices en-route. Fourthly, a safety analysis was performed following the ‘Swiss Cheese Model’ [6] and possible mitigation measures are proposed.

1.1. Simulation Design

The aim of the simulation is to identify aircraft which potentially experienced wake turbulence. The surveillance data is used in order to recreate the flown trajectories of each aircraft. The corresponding wake vortex trajectory was computed for each of the flown trajectories. The wake vortex trajectory was broken down into seven segments, each defined by a volume. The size of these wake vortex volumes are based predominantly on the uncertainty of the aircraft position and therefore these volumes are referred to as wake vortex habitation areas. These are areas where the wake vortex could have been. The trajectories of all other aircraft are cross-checked with these wake vortex habitation areas in order to identify potential conflicts. A preliminary study of the wake turbulence reports showed that International Civil Aviation Organization (ICAO) Wake Turbulence Category (WTC) 'Heavy' aircraft are responsible for 82% of the reported wake vortex encounters. This can be explained by the fact that heavier aircraft generate stronger wake vortices, hence they can induce more severe wake turbulence. Therefore this simulation computes only the wake vortex trajectories of all the 'Heavy' aircraft.

The weight and the lift distribution of the generating aircraft significantly influence the wake vortex trajectory. However, both parameters may vary for different aircraft types and may also vary depending on the phase of flight. These parameters are not present in the surveillance data and are often considered confidential by airline manufactures and operators. To cope with this, an assumption has been made with respect to lift distribution. Since this study only considers en-route aircraft above FL285, it was assumed that the lift distribution of all aircraft is elliptical. A range of possible weights was considered in order to cope with the unknown weight of the aircraft. This range includes seven possible weights, ranging from 65% Maximum Take-off Weight (MTOW) to 95% MTOW in steps of 5% MTOW. The wake vortex trajectory varies for each weight and therefore the simulation performs the wake vortex trajectory computation for each of the seven weight combinations. For each wake vortex trajectory, aircraft are identified which intersect the wake vortex habitation area. Once an aircraft has been identified to intersect a wake vortex habitation area, it is referred to as a potential wake vortex encounter.

The severity was computed for each potential wake vortex encounter. Severity for the purposes of this study is defined by the Rolling Moment Coefficient (RMC). This is a well-documented severity criteria and it is also used in Re-categorization of the ICAO Wake Turbulence Separation Minima Europe (RECAT-EU) [3, 8, 13, 12]. The approach used by RECAT-EU was designed for approach and departure conditions. Therefore one important adjustment was made before applying it to this en-route simulation. In RECAT-EU, the wake vortex system consisted of a single vortex; in this study a double vortex system was adopted.

The simulation framework is validated using 12 of the 26 wake turbulence reports collected from EUROCONTROL Voluntary ATM Incident Reporting (EVAIR). For these 12 wake turbulence reports both surveillance and meteorological data is available and there is sufficient information in the report to confirm the aircraft which were involved in the safety occurrence. The reported wake vortex encounters should be listed as one of the potential wake vortex encounters in the simulation results.

1.2. En-route Wake Vortex Encounter Frequency

The probability of encountering a wake vortex during the en-route flight phase in European airspace was determined by simulating the wake vortex trajectories for 24 days of historical surveillance data. The time periods studied are listed in Table 1.

Table 1. Dates simulated to determine the wake vortex encounter frequency.

Time Periods		
21 - 25	April	2011
15 - 20	August	2011
08 - 13	September	2011
06 - 12	February	2012

These time periods have been selected for this study based on the specific meteorological conditions at that time. Together, these 24 days include over 400,000 flights. For date the number of potential encounters is computed using the simulation framework. The number of potential encounters is corrected with two factors. The first factor is related to the fact that the wake vortex habitation area is much larger than the actual wake vortex hazard area. The size of the wake vortex hazard area is typically the size of an aircraft. However, several uncertainties are taken into account in this simulation, such as the position uncertainty of aircraft. Therefore the wake vortex habitation area is much larger than the actual size of the wake vortex; this is illustrated in Figure 1. The size of the wake vortex hazard area is approximately 1% of the simulation wake vortex habitation area.

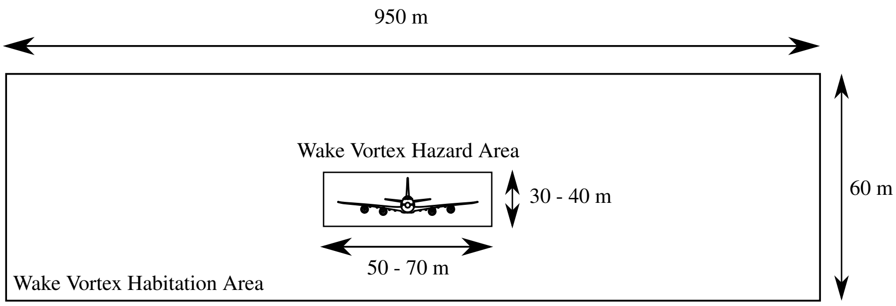


Figure 1. Comparison of the potential wake vortex habitation area with respect to actual wake vortex hazard area (drawing is not to scale).

The second factor relates to the fact that not every weight combination results in a wake vortex encounter. In these 24 simulations, it was observed that on average 60% of the weight combinations result in a potential wake vortex encounter. The total number of potential encounters is corrected by this factor since the weight of the generating aircraft can vary from Operational Empty Weight (OEW) up to MTOW.

1.3. Influencing Factors

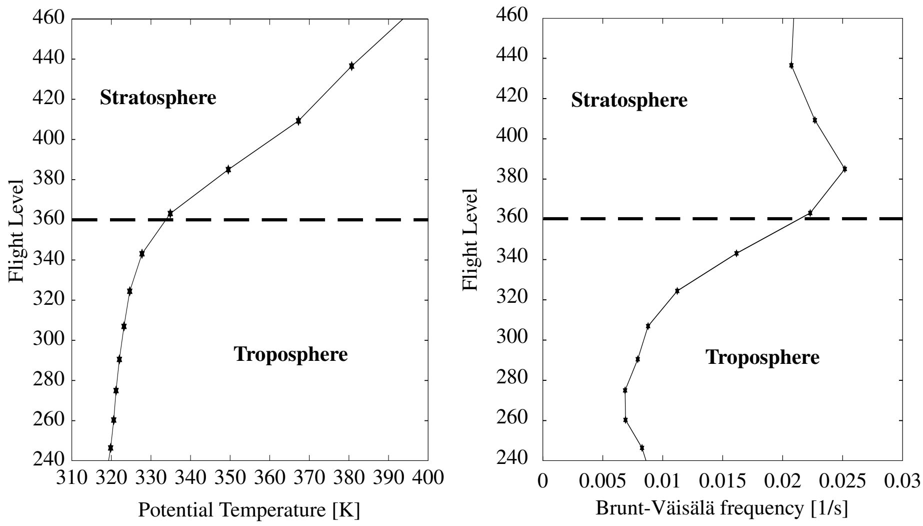
To analyse the main factors which influence the risk of wake vortex encounters, the results from the simulations were compared to the 26 reported wake vortex encounters. Even though a report rate of 26 reports over 3 years is considered low, there is reasonable confidence that these reports present a representative view of the en-route wake vortex encounters. This confidence is based on the fact that over 200 airlines provide their incident reports to EVAIR [2].

Three factors have been identified in this study. The first has already been mentioned, namely that ICAO WTC ‘Heavy’ aircraft can generate wake vortices strong enough to induce severe wake turbulence. The other two factors which are analysed further are the encounter geometry and the atmospheric conditions. The encounter geometry is classified into four groups, depending on the flight mode of the aircraft involved in the encounter. These four different encounter geometries are listed in Table 2.

Table 2. Encounter geometries, aircraft 1 and 2 refers to either the generating or the encountering aircraft.

Encounter Geometry	Aircraft 1	Aircraft 2	Vertical Separation
1	Climb/Descent	Level	any
2	Climb/Descent	Climb/Descent	any
3	Level	Level	< 1000 feet
4	Level	Level	≥ 1000 feet

The atmospheric condition which has the greatest effect on the evolution of the wake vortex is the stratification, frequently described by the Brunt-Väisälä frequency. This parameter depends mainly on the potential temperature and the potential temperature lapse rate. A preliminary analysis showed that the thermal tropopause height, defined by the WMO, could be used as an indirect measure for the stability of the atmosphere. In Figure 2, a vertical potential temperature profile is shown with the corresponding Brunt-Väisälä frequency profile. In Figure 2(b) it can be seen that this frequency is generally lower than in the stratosphere. A higher Brunt-Väisälä frequency indicates a higher level of stability and the buoyancy force acting on the wake vortex will be larger, which tends to increase the decay of the wake vortex.



(a) Potential temperature at cruise altitudes.
(b) Brunt-Väisälä frequency at cruise altitudes.

Figure 2. Potential temperature and corresponding Brunt-Väisälä frequency for a vertical temperature profile with the thermal tropopause at FL360.

The effect of the tropopause is studied separately by imposing six different temperature profiles, each with a different tropopause height. The probability of an encounter is determined on the basis of seven days of surveillance data for each temperature profile.

1.4. Safety Analysis

The 'Swiss Cheese Model' approach, also known as the barrier model, has been used to assess the safety of various ATM hazards. These ATM hazards include Mid-air Collision, Runway collision, Controlled Flight into Terrain and Taxiway [5]. A barrier model shows which actors and procedures help to prevent the occurrence of a safety event. The barrier model approach is used to analyse which actors and procedures currently prevent severe wake vortex encounters. Based on this analysis, potential mitigation measures are proposed for the near and distant future.

2. Analysis and Results

The most important result concerns the validation analysis. The validation showed that the simulation is capable of reproducing 9 out of 12 (75%) of the reported incidents. These results are discussed first, followed by the results of the study into the probability of a wake vortex encounter. After this, the two factors which influence the en-route wake vortex encounter risk are discussed, followed by an analysis of how they are expected to evolve in the future.

2.1. Validation

The simulation is able to reproduce 9 out of 12 reports. The severity of these incidents was estimated by the simulation on the basis of weather conditions and wake vortex age. In Figure 3 the severity of the encounters is shown in terms of the RMC, for each of the nine cases. There is an uncertainty with respect to determining the RMC. One of the most important uncertainties here is the weight of the generating aircraft, which is described in Section 1.1. In some cases, several weight combinations of the generating aircraft result in a potential encounter. In such cases, there is a large variation possible in the strength of the wake vortex, since it depends on the weight of the generating aircraft. This large variation in wake vortex strength is directly responsible for the uncertainty in the RMC of the encounter.

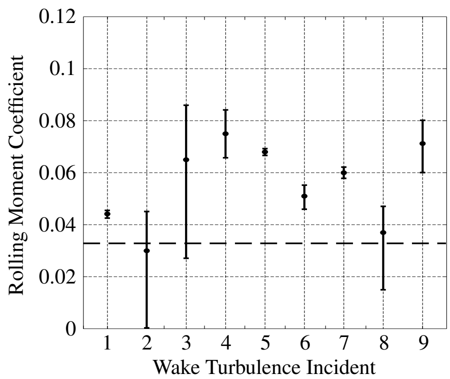


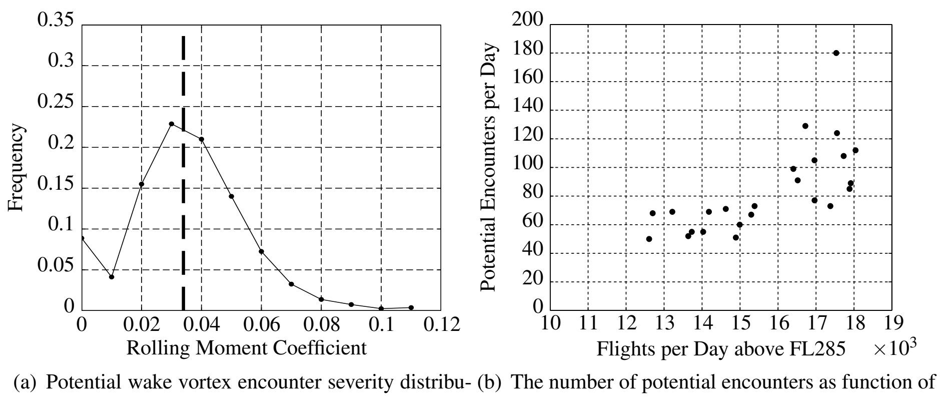
Figure 3. Estimated RMC of the reported incidents.

RECAT-EU considered several different studies which examined acceptability threshold in terms of the RMC. The acceptability threshold in terms of RMC for RECAT-EU is 0.03 and 0.035 [3]. Pilots who experience wake turbulence characterized by a RMC value above this threshold are likely to report it, since it is likely to be perceived as hazardous.

Three reported incidents were not reproduced by the simulation. In two cases, this was a result of the interpolation method used between individual surveillance data points. A linear interpolation is currently used for interpolating the altitude variation between data points. The time resolution of the surveillance data varies between 1 to 3 minutes. The accuracy of this approach depends strongly on the actual climb or descent trajectory. However, this is not considered to invalidate the simulation, since in some cases this linear interpolation is a better approximation of the actual trajectory than in order cases. Because of this, the simulation will sometimes generate encounters which may not have occurred. The third report which was not reproduced is the only real failure of the simulation; in this case the descent rate of the wake vortex was underestimated. According to the wake vortex model, the descent rate could range between 2 and 3 meters per second. After analysing the wind speed and direction and the radar tracks of both aircraft, it is concluded that the wake vortex would have to descent at a rate of 5-10 meters per second in order to reach the encountering aircraft. It is believed that vertical wind, which is not taken into account in this simulation, could account for this increased descent rate. In a previous study [1], it was also observed that in one case the wake vortex appeared to have descended faster than predicted by the wake vortex model. This shows that further research is required to determine whether vertical down drafts or another phenomenon are responsible for this increased descent rate.

2.2. Wake Vortex Encounter Probability

The probability of a wake vortex encounter was determined on the basis of the 24 simulation runs. Figure 4(b) shows the potential wake vortex encounters per day. The severity for each of these potential encounters is computed by the simulation. The average severity distribution based on these 24 simulations is shown in Figure 4(a).



(a) Potential wake vortex encounter severity distribution.

(b) The number of potential encounters as function of the number of flights per day.

Figure 4. The severity distribution and the number of potential encounters identified, per simulated day.

The probability of a wake vortex encounter above FL285 can be estimated using the information in both of these graphs and the uncertainties described in Section 1.2.

The probability for three types of wake vortex encounters were distinguished, namely encounters of any severity, encounters with a severity above the acceptability threshold [3], and encounters categorised as severe, with an RMC above 0.07. The probability of occurrence of these encounters is listed in Table 3. This data can also be converted to show how many encounters will occur per day, assuming that there approximately 16,000 flights on average in the 24 days under consideration. Table 3 shows that in such cases wake vortex encounters occur, depending on the severity, anywhere between once every 2 to once every 38 days.

Table 3. Probability of an en-route wake vortex encounter above FL285.

Induced RMC	**Encounter frequency**	**Wake Vortex Encounters**
Any RMC	3.3×10^{-5} per flight	1 every 2 days
RMC > 0.03	1.5×10^{-5} per flight	1 every 4 days
RMC > 0.07	1.6×10^{-6} per flight	1 every 38 days
Wake turbulence reports	-	1 every 40 days

2.3. Encounter Geometry

In the wake vortex reports, the encounter geometry which occurs in 64% of the cases involves one or both aircraft climbing or descending. A similar result is indicated by the simulation. The encounter geometry where both aircraft are in level flight with 1000 feet of vertical separation occurs in 27% of the reported cases. However, in the simulation only 3% of the encounters occur when both aircraft are in level flight with 1000 feet of vertical separation. As mentioned before, observations have been made which suggest that the wake vortex may descent faster than predicted by the model. The fact that the simulation suggests fewer scenarios in which both aircraft are in level flight may also indicate that there is an important aspect missing in the simulation. This aspect is one which is likely to influence the descent rate of the wake vortex.

It is important to note that both the simulation and the reports indicate that climbing and descending aircraft play an important part in the risk of encountering a wake vortex. The en-route wake vortex encounter study performed for RVSM already highlighted this in 1999 [14]. The reason why encounters are more likely when one of the aircraft is climbing or descending is the fact that this scenario can occur regardless of the weather. A wake vortex encounter can also occur when both aircraft are in level flight with a 1000 feet vertical separation. Contrary to the first scenario, these types of encounter depend on both the weather conditions and the characteristics of the generating aircraft. The difference between these two scenarios is best illustrated by discussing two examples, one example where the generating aircraft is climbing and the encountering aircraft is at level flight and one where both aircraft are at level flight.

The first important aspect to realize is that the wake vortex descents with respect to the trajectory of the aircraft. This is illustrated in Figure 5, where the generating aircraft is climbing at 1500 feet per minute and the wake vortex is descending at 500 feet per minute. Here it can be clearly seen that at a wake vortex age of 30 seconds, the wake vortex can be encountered even when a separation of 5 nautical miles is applied. At a wake age of 30 seconds the strength of the wake vortex will be independent of the weather conditions. At that time the wake vortex is still strong and can be expected to be close to the strength at the time of generation. Furthermore, no strong descent speed is required since the wake vortex is already generated at the altitudes of the other aircraft.

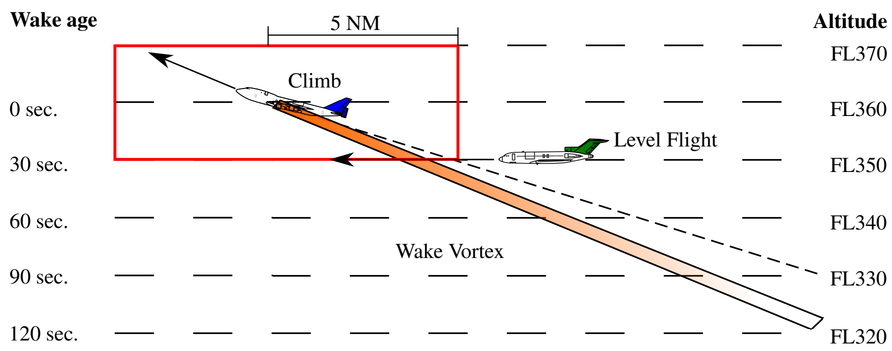


Figure 5. Generator climbing in front of encountering aircraft.

The geometry in which both aircraft are at level flight is significantly different. In fact this scenario only occurs when there are favourable atmospheric conditions for the wake vortex decay and when the generating aircraft has a certain combination of wingspan and weight. The wake vortex model shows that the wake vortex of aircraft with a MTOW above 350,000 kilograms can potentially descend over 1000 feet under favourable atmospheric conditions. In Figure 6 it can be seen why this is the case. First of all, the wake vortex needs a strong initial descent rate in order to reach the next flight level. Secondly the decay has to be low, otherwise the wake vortex will dissipate before it reaches the next flight level. This scenario is therefore dependent on both the generator characteristics and the meteorological conditions.

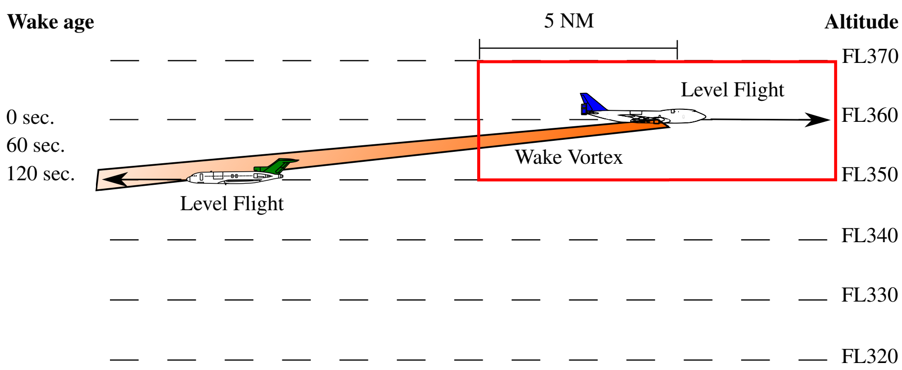
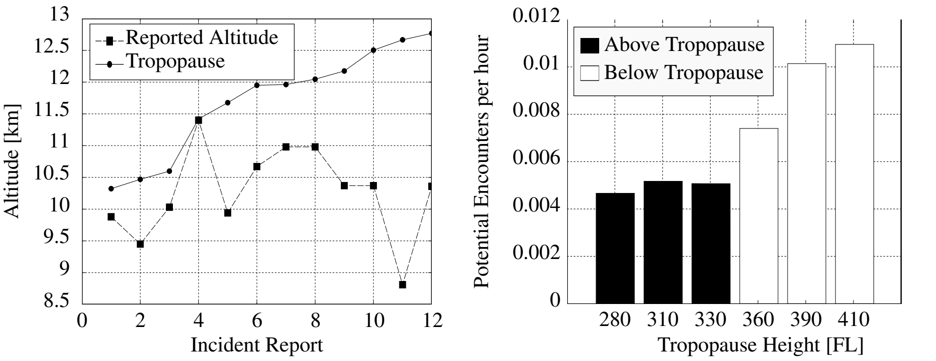


Figure 6. Generator crossing 1000 feet above the encountering aircraft.

2.4. Atmospheric influences

In Section 2.3 it is shown that the meteorological conditions, especially the vertical stability play a role in wake vortex encounters. In Section 1.3 it is shown that the vertical stability characteristics are different above and below the tropopause. The generally lower stability in the troposphere provides favourable conditions for the evolution of the wake vortex. An analysis of the reported wake vortex encounters showed that all 12 reports of the validation case occurred in the troposphere region of the atmosphere (as shown in Figure 7(a)). The simulation framework revealed that the probability of encountering a wake vortex is generally larger in the troposphere than in the atmosphere. A specific example may be used to illustrate this. The probability of a wake vortex encounter is computed for aircraft flying at FL340 for each of the six different temperature profiles. The resulting probability is shown in Figure 7(b). The black bars in this figure indicate that FL340 is above the tropopause and the white bars indicate that FL340 is below the tropopause. This figure shows that when FL340 is below the tropopause, the probability increases. The reason this increase continues is because the stability of the atmosphere does not change instantaneously. In the temperature profile seen in Figure 2, it can be seen that the Brunt-Väisälä frequency has a transition zone which is located approximately 3000-5000 feet below the tropopause. The severity of the encounters also increases for an increasing tropopause height. It is important to note that the tropopause is not located at one constant altitude. It varies in time and is influenced by several factors such as weather systems. On average the tropopause is located higher near the equator and is lower near the poles.



(a) Wake vortex encounter altitude and the tropopause height at the time of the encounter.

(b) Number of potential encounter per hour of flight at FL340 for six temperature profiles.

Figure 7. The reported altitude of the wake turbulence incidents and the result of the tropopause study.

2.5. Risk Evolution

It is thought that the risk may increase in the future. This is based on the evolution analysis of three parameters; the evolution of the number of movements, evolution of the tropopause and the evolution of the traffic mix.

According to the seven-year forecast performed by Statistics and Forecast Service (STATFOR), the number of movements is expected to grow at a stabilized rate of 3% per year [4]. With an increasing number of movements, the risk of encountering a wake vortex increases quadratically. Therefore the evolution of the number of movements is expected to contribute to an increased risk of encountering a wake vortex en-route.

Several climate change studies indicate that the tropical regions of the atmosphere are expanding towards the poles. The rate between individual studies varies, however all studies agree that the tropics are expanding. An estimate of the expansion rate is 1 degree latitude per decade according to Reichler [7]. This means that it can be expected that the tropopause may on average rise within European airspace. This could result in more en-route wake vortex encounters in the future and may contribute to an increased severity of the wake vortex encounters.

Furthermore, there are constant changes in the traffic mix within European airspace. In the last decade, new 'Super Heavy' aircraft have been introduced. It is expected that the traffic mix will keep evolving and the range of aircraft types will keep diversifying. Especially when the number of Heavy aircraft increases along with the introduction of Medium, Light and Very Light aircraft, an increased risk is to be expected with respect to wake vortex encounters during the en-route phase of flight.

3. Target Level of Safety (TLS) and Mitigation Measures

The Target Level of Safety (TLS) must be defined in order to explicitly define whether the current level of safety with respect to en-route wake vortex encounters is acceptable. Since there is currently no TLS for en-route wake vortex encounters, it is impossible to quantify whether the number of occurrences and severe occurrences is at an acceptable level today.

Therefore this study performed an analysis of barriers which currently exist in the ATM. The results of this analysis are discussed in Section 3.1. The risk of en-route wake vortex will evolve in the future, as discussed in Section 2.5. Furthermore, one of the goals of the ATM Master plan is to increase safety by a factor of 10 [9]. Therefore, mitigation measures are proposed which can support a reduction of the risk. There are two classes of mitigation measures which are proposed here, short-term and future measures. The short-term measures are based on the technology and knowledge which is available today and which can therefore be implemented on a short time scale. These are discussed in Section 3.2. The future measures are proposed in Section 3.3. These measures include technologies and procedures which would have to be researched and developed.

3.1. Analysis of the current ATM

Five barriers are distinguished in this barrier model.

1. Strategic Conflict Managemet (SCM)
2. Air Traffic Flow and Capacity Management (ATFCM)
3. Pre-Tactical Conflict Management (PTCM)
4. Tactical Conflict Management (TCM)
5. Pilot and Aircraft Reaction

Each of these barriers contains many defensive layers: some are engineered (alarms, physical barriers), others rely of people (pilots and Air Traffic Controllers (ATCO's)) and yet others depend on procedures. The aim of each barrier is to minimize the probability that a conflict hazard develops into an accident or a severe incident.

The most effective barrier today is the SCM barrier. This barrier contains procedures which include the vertical and radar separation minima. These two separation minima ensure that there is a minimum separation between aircraft and this reduces the chance of encountering severe wake turbulence. When RVSM was introduced in 2002, the en-route wake vortex hazard was taken into consideration [14]. In Section 2.3 it was also observed that wake vortices can potential descent 1000 feet below the generation altitude under specific conditions, namely when the MTOW of the generator is greater than 350,000 kg and when flying in atmospheric regions with low vertical stability (3000-5000 feet or more below the tropopause). Since the introduction of RVSM, the traffic mix has evolved and currently there are more 'Super Heavy' aircraft using the airspace. This reduces the effectiveness of this barrier since the specific conditions mentioned above are more likely to occur.

The ATFCM barrier also mitigates the risk of wake vortex encounters. This barrier synchronizes air traffic throughout the European airspace. It is important to realize that the primary aim of this barrier is to optimize the capacity of the airspace, and this does not explicitly consider wake turbulence. The two barriers are the PTCM and the TCM barrier. The short-term mitigation measures are focussed mainly on these two barriers.

3.2. Short term mitigation measures

Two approaches should be considered for reducing the risk in the near future. One is to reduce the severity of wake vortex encounters, and the second is to reduce the probability of a wake vortex encounter. To improve the level of safety on a short time scale it is best to focus on the last three barriers, the PTCM, TCM and the pilot reaction. The main actors in these barriers are the ATCO's and the pilots. There are three steps which can help to mitigate the likelihood of a wake vortex encounters. These three steps are recognition, anticipation and best practices. Pilots and ATCO's can be briefed on the operational conditions which increase the hazard of a wake vortex encounter. This way they can recognize operational scenarios which may result in a wake vortex encounter. When they recognize such a scenario, they can anticipate a wake vortex encounter. Finally best practices can be introduced and briefed to them such that the conflict can be avoided or that the severity of the conflict can be minimized.

In order to recognize and anticipate hazardous situations it is important for pilots and ATCO's to have a high situational awareness with respect to other traffic and the meteorological conditions, since the three main influences are related to other traffic and weather. There are a couple of tools currently available to pilots and ATCO's which can facilitate this awareness, these tools are listed below.

- History dot function for Air Traffic Control (ATC);
- Cockpit navigation display;
- Radio communication and visibility;
- Significant weather chart, for tropopause information during pre-flight and/or pre-shift briefing.

ATCO's and pilots can be briefed on how these tools can aid them to recognize, anticipate and possibly avoid wake vortex encounters. As a result of anticipation a wake vortex encounter, they will be able appropriately respond to a wake vortex encounter, hereby avoiding an adverse reaction of the aircraft due to the pilot reaction. This way the last three barriers will be more effective.

Best practices could be developed to assist the decision-making of pilots and ATCO's when they recognize potentially hazardous situation. The first mitigation measure which can be taken by a pilot is turning on the seat belt sign. Wake turbulence reports over the past three years show that passengers have a high risk of getting injured, and simply turning on the seat belt sign will avoid most injuries. Pilots could also try to avoid an encounter. Wake vortices are transported by wind, thus an encounter is likely to be avoided by remaining upwind of the 'Heavy' aircraft. The offset distance could be in the order of a couple of hundred meters. Pilots have actual wind information (direction and speed) available in the cockpit on the Navigation Display. When ATCO's recognize such a scenario, they could advise the pilots of the 'Heavy' traffic ahead so that the awareness of the crew is raised to the potential wake vortex hazard in front.

3.3. Future mitigation measures

In the future technologies could be developed to support wake vortex avoidance. Such technologies may include advanced warning (5-15 minutes) through wake vortex prediction based on models for pilots and ATCO's and wake vortex detection by on-board sensors. The use of wake vortex models can also be extended into the ATFCM barrier if capacity management is based on the 4D trajectory of the aircraft. In such cases, wake vortex models could be included to predict the approximate location and strength of a wake vortex. For the future ATM, it is also possible to further develop best practices for climbing and descending aircraft.

4. Discussion

This study showed that the wake turbulence report rate is low. The results of the simulation framework indicate that the frequency of occurrence may be higher than is currently reported. There is good reason to believe that the EVAIR reports are representative of reporting throughout Europe due to the large number of airliners which are linked to EVAIR [2]. Nevertheless, it is important to note that it is not mandatory to report wake turbulence. It is therefore possible that pilots are not reporting wake vortex encounters systematically and it might also be possible that pilots do not recognize turbulence as wake turbulence and therefore do not report it as such.

In terms of reproducing the reported wake vortex encounters, it should be noted that there are three reports which were not reproduced. One of these was a failure of the simulation. In this case the descent rate determined using the wake vortex model was too low to result in an encounter. In a previous study [1] this was also observed and it is possible that a phenomenon is occurring en-route which is not yet taken into consideration by this simulation. Vertical winds are believed to be one of the plausible reasons for this, and this should be the subject of further investigations.

5. Conclusion and Outlook

This paper presents a simulation framework which can identify potential en-route wake vortex encounters. It was found during this work that the risk is influenced by three factors. The first relates to ICAO WTC 'Heavy' aircraft, which can potentially induce severe wake turbulence. Secondly, aircraft which are climbing or descending behind a 'Heavy' aircraft or 'Heavy' aircraft which are climbing or descending in front of other traffic have an increased risk of encountering or inducing wake turbulence respectively. It is important to stress that these encounters can occur, regardless of the generator weight or atmospheric conditions. This is because the wake vortex can be encountered when the wake vortex age is well below one minute. Thirdly, when flying below the tropopause, the atmospheric conditions are generally favourable for the wake vortex to remain strong for a longer period of time. In such cases the wake vortex of aircraft with a MTOW larger than 350,000 kilogram, may potentially descend one flight level lower.

Even though the reporting rate is currently low at en-route altitudes, it is not possible to explicitly state whether it is acceptable. Nevertheless, some mitigation measures have been proposed which could be adopted to decrease the risk of en-route wake vortex encounters. These measures are based on recognition, anticipation and best practices. This means that pilots and ATCO's could recognize and anticipate these situations and avoid or mitigate them. A straightforward way of reducing the severity of the encounter is by turning on the seat belt sign whenever a pilot recognizes a situation which could potentially result in an encounter. Further steps to avoid a wake vortex can also be taken if the pilots take an upwind off-set of a few 100 meters with respect to the trajectory of the 'Heavy' aircraft.

It should be the aim of future research to determine a TLS. Furthermore, it is important to develop an objective wake turbulence severity scheme so that pilots can objectively assess the severity of the encounter. It is also recommended that pilots should be encouraged to report wake vortex encounters. Additional research can focus on the use of wake vortex models en-route. In this study it was observed that in one case the descent rate of the wake vortex was probably much higher than predicted by the wake vortex model. Research can be directed at improving the wake vortex models for en-route applications.

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