



Directed study on in-flight turbulence

Final report

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Short abstract: A directed study on in-flight turbulence events and their impact on flight safety and flight operations was performed by means of the Data4Safety (D4S) programme. D4S is a data collection and data analysis programme for management of safety risks at European level, established in partnership with EASA, airlines, manufacturers, ANSPs, authorities, and airports. Using occurrence reports and flight data samples from the D4S programme, the directed study collected and analysed turbulence events to assess the prevalence of turbulence events and their impact on e.g. injury and aircraft damage levels, operational consequences and mitigation measures.

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Acronyms

Acronym	Definition
ADS-B	Automatic Dependent Surveillance–Broadcast
AI	Artificial Intelligence
ANSP	Air Navigation Service Provider
ATC	Air Traffic Control
ATM	Air Traffic Management
CAT	Clear-air Turbulence
D4S	Data4Safety (programme)
DAGO / DaGo	Data Governance
ECR	European Central Repository
ERCS	European Risk Classification Scheme
FDM	Flight Data Monitoring
FDR	Flight Data Recorded
FL	Flight Level
IFR	Instrument Flight Rules
JSON	JavaScript Object Notation
LLM	Large Language Model
MMO	Maximum operating Mach number
NAA	National Aviation Authority
NM	Nautical Mile
QAR	Quick Access Recorded
RMS	Room Mean Squared
SPI	Safety Performance Indicator
TCAS (RA)	Traffic Collision Avoidance System (Resolution Advisory)
TF-IDF	Term Frequency-Inverse Document Frequency
VMO	Maximum operating velocity

EXECUTIVE SUMMARY

Description of Work

This report presents a directed study on in-flight turbulence carried out within Task 2.1 of the ALBATROS project, using the data and analytical capabilities of the Data4Safety (D4S) programme. The study characterises turbulence encounters during the climb, cruise and descent phases of commercial air transport operations and examines their consequences for flight safety and flight operations. Two complementary safety data sources were analysed: text-based occurrence reports from the European Central Repository (ECR), normalised against Eurocontrol exposure data to derive occurrence rates, and a large body of recorded flight data (approximately 4.4 million flights from six European operators), which provides an objective measure of physical exposure to turbulence. Each source was processed through a dedicated, purpose-built methodology. Large language models (LLMs) were used to extract additional information from the ECR narratives, while a method based on the root mean square of the vertical load factor (N_z) signal was developed to identify turbulence episodes in the recorded flight data. The study characterises turbulence encounters, such as frequency of occurrence, distribution of turbulence by type of turbulence, intensity level, flight phase, and geographical region. In addition, the consequential events associated with turbulence were identified and analysed in both datasets, including injury and damage. Finally, the performance of safety barriers using the European Risk Classification Scheme (ERCS) framework was assessed using the ECR data.

Problem Area

In the coming decades, aviation must accommodate growing demand while managing a range of emerging hazards, among which weather remains an important safety concern. Climate change is expected to affect trends in hazardous weather phenomena, including changes in their frequency, intensity, geographical distribution and variability, potentially magnifying existing safety risks and creating new ones. In this context, EASA has identified severe turbulence, both within cloud and in clear air, among the weather-related hazards requiring further investigation [1]. Turbulence is already a significant safety concern for aviation and was identified by ICAO as the leading cause of aviation accidents in 2023 [2]. Turbulence encounters are expected to increase in both frequency and intensity over the coming decades as a consequence of climate change. Therefore, there is a need to better understand and characterise turbulence and its effects on flight safety, so that current safety levels can be maintained. The Data4Safety programme, coordinated by EASA as a common European platform for safety data collection and analysis, provides an opportunity to address this need. This directed study was undertaken to use the capability of the D4S platform for a research study addressing turbulence and establishing a baseline turbulence assessment.

Results & Conclusions

The study combines two complementary sources of safety information. The European Central Repository (ECR) provides a picture of reported turbulence encounters, including their circumstances and

consequences, and is therefore particularly informative about the visible safety risk associated with turbulence. Recorded flight data, by contrast, capture the physical exposure to turbulence across flights, irrespective of whether an encounter resulted in a reportable consequence. Neither source alone provides the complete picture; their combination allows the frequency and characteristics of physical turbulence exposure to be considered alongside the consequences observed in operations.

Turbulence exposure is frequent, but predominantly light

The recorded flight data shows that turbulence affects approximately 18% of flights. More than 97% of identified turbulence episodes are of light intensity, while severe turbulence accounts for only around 0.1% of episodes. For an individual flight, therefore, turbulence is an infrequent and predominantly benign exposure. Aircraft damage is rare, and the vast majority of turbulence encounters do not result in a significant safety consequence.

The ECR provides a different picture, with reported occurrences strongly skewed towards events with consequences as a result of reporting requirements and reporting practices. The intensity scales used by the two sources are fundamentally different and cannot be matched on an event-by-event basis. The fact that their aggregate exposure estimates become closer towards the severe end of the intensity spectrum should therefore not be interpreted as evidence that the two scales are equivalent. Rather, it is consistent with the consequence-driven nature of ECR reporting: stronger physical turbulence is more likely to produce consequences that warrant reporting, and the ECR can consequently be expected to reflect the behaviour of physical turbulence exposure more closely as severity increases.

The distribution of turbulence differs from the distribution of reported consequences

The recorded flight data show that turbulence exposure is concentrated towards lower altitude bands and particularly towards the end of the flight, with around 70% of turbulence episodes occurring during descent and approach. Cruise has the lowest turbulence encounter rate per unit of flight time. The ECR presents a markedly different distribution: almost half of reported turbulence occurrences take place during cruise.

This difference is significant because cruise combines two conditions that increase the potential for consequences. Clear-air turbulence is difficult to anticipate using conventional weather radar, while the cabin during cruise is more likely to be active, with occupants standing, walking, using the lavatory or performing cabin service rather than being seated and restrained. The contrast between the physical exposure profile and the reported-occurrence profile therefore illustrates the importance of considering both the frequency of turbulence and the circumstances in which it occurs.

A further concentration of turbulence episodes is observed around the top of descent in older-generation aircraft but not in newer aircraft. The association with aircraft generation points to weather-radar capability as a plausible contributor and highlights the transition from cruise to descent as a phase in which timely turbulence information and cabin preparation are particularly important.

Clear-air turbulence is particularly relevant to injury risk

Clear-air turbulence (CAT) is associated with a higher likelihood of occupant injury. This does not appear to be because CAT is inherently more intense than other forms of turbulence, but because it is more difficult to anticipate and occurs predominantly during cruise, when cabin activity and the proportion of unrestrained occupants are higher.

The findings therefore reinforce the importance of obtaining and disseminating turbulence information as early and reliably as practicable. Where an encounter can be anticipated, the flight crew can take avoidance or mitigation measures and the cabin crew can suspend service, secure the cabin and ensure that occupants are appropriately restrained. For passengers, consistent use of seatbelts is particularly important: unrestrained passengers are at least three times more likely to be injured and are also more likely to sustain serious injury. For cabin crew, who cannot remain restrained while performing their duties, timely turbulence information and the ability to secure the cabin before an encounter are particularly important.

Consequences increase sharply with turbulence intensity

Consequential events become substantially more frequent as the intensity of the aircraft response to turbulence increases, with consequential-event rates increasing by one to two orders of magnitude from light to severe intensity. This confirms that the relatively rare, stronger encounters are associated with a greater concentration of safety-relevant consequences.

The consequences identified in the ECR are varied. Overspeed is the most frequently reported consequence, occurring in approximately one quarter of turbulence-related occurrences, followed by injuries, aircraft upset and operational consequences such as diversions. Aircraft damage and loss of separation are comparatively rare. In the recorded flight data, autopilot disengagement is the most frequently detected consequential event.

The two sources therefore provide complementary information on different manifestations of turbulence. The ECR identifies consequences that become visible through operational reporting, while recorded flight data provide a broader picture of aircraft response, including events that do not necessarily result in a reportable occurrence.

Turbulence protection relies on multiple, complementary barriers

The safety-barrier analysis shows that protection against turbulence does not depend on a single barrier but on a layered combination of technical, operational and human measures. These include access to turbulence information and situational awareness, timely flight deck and cabin actions, occupant restraints, aircraft structural and flight-envelope protections, warning systems and recovery measures.

The ECR provides only a partial view of this barrier system. Because it contains, by definition, reports of turbulence encounters that did occur and generally does not capture turbulence that was successfully

avoided, preventive barriers are inherently under-represented, while mitigation and recovery barriers are more readily observed. The analysis should therefore not be interpreted as an assessment of preventive-barrier effectiveness based on their apparent presence or absence in reported events.

A reported consequence also does not necessarily mean that all relevant barriers failed. Different barriers address different effects of an encounter. Aircraft-state events such as overspeed, aircraft upset and level bust are primarily limited by structural and flight-envelope protection, crew monitoring and warning-system responses. These protections may operate successfully even when an occupant injury occurs. Conversely, the use of restraints and timely cabin preparation—including suspending cabin service and conducting a cabin safety check—reduce the likelihood and severity of turbulence-related injuries but cannot necessarily prevent aircraft-state changes caused by the encounter.

Principal conclusions

Three principal conclusions emerge from the results.

First, turbulence is predominantly a low-intensity and low-consequence exposure, but the safety risk is concentrated in specific circumstances. Stronger encounters are more likely to produce consequences, but injury risk is also strongly influenced by whether turbulence can be anticipated and whether the cabin and its occupants are prepared. The study therefore identifies turbulence management not simply as a question of turbulence intensity, but as a question of exposure combined with the circumstances of the encounter.

Second, timely turbulence information and appropriate preparation are central to effective mitigation. For passengers, consistent seatbelt use is the most important protection against injury. For cabin crew, timely information is critical because it allows cabin service to be suspended and the cabin to be secured before an encounter. More broadly, the findings reinforce the value of turbulence detection, forecasting, avoidance and early preparation, particularly for clear-air turbulence and during the transition from cruise to descent.

Third, turbulence protection is most effective when multiple barriers operate together. The study does not identify a single measure capable of preventing all turbulence-related consequences. Effective management depends on the coordinated use of available turbulence information, flight deck and cabin preparation, occupant restraints, aircraft structural and flight-envelope protections, warning systems and recovery capabilities. The occurrence of a reported consequence should therefore be understood in the context of the specific effect and the barrier intended to prevent or mitigate it.

Implications of a changing climate

The current findings also provide a baseline against which future changes in turbulence can be assessed. There is a strong and growing scientific consensus that anthropogenic warming is increasing in-flight turbulence, with the most consistent evidence concerning clear-air turbulence. Severe CAT is projected to

become substantially more frequent under future climate scenarios, while convective turbulence is also expected to intensify as a warmer and moister atmosphere increases the energy available to severe thunderstorms.

This reinforces the importance of continued improvement in the detection and forecasting of clear-air turbulence, where low predictability combines with high cabin activity, as well as continued development of onboard weather-radar capability for the management of convective turbulence. The baseline established by this study provides a basis for monitoring how turbulence exposure and its associated consequences evolve as weather patterns, technology and operational practices change.

Applicability

The findings apply to European commercial air transport operations and provide a baseline turbulence assessment for the climb, cruise and descent phases. Airlines are encouraged to use the results in their review of turbulence risk. Furthermore, airlines are recommended to evaluate the applicability of the methodology for identifying and analysing turbulence episodes in recorded flight data within their Flight Data Monitoring (FDM) programmes. The bow tie model may be used by airlines to identify factors and events for which data needs to be collected within the airline through for example Flight Data Monitoring (FDM) or occurrence reporting systems.

The analytics developed in this study should be operationalised as safety performance indicators (SPIs) within the D4S platform, so that turbulence can be monitored continuously at European level. This would facilitate a transition from European safety research to ongoing, real-time safety monitoring, enabling proactive identification of emerging turbulence trends and risks.

The study represents the first attempt of its kind to combine ECR occurrence reports with recorded flight data to characterise in-flight turbulence, and, in the volume and diversity of the data brought together, it is without known precedent in the study of this hazard. Neither source alone could provide the complete picture obtained in this study: ECR data capture reported occurrences and their consequences, while recorded flight data provide an assessment of turbulence exposure and aircraft response across a large and diverse set of European flights. The combination of these sources therefore provides a stronger basis for understanding turbulence and demonstrates an approach that could be applied to other safety issues. A central conclusion of this study is that the data assets and analytics made available through the D4S programme have reached a level of maturity at which they can support a research study of this kind for the benefit of, and in collaboration with, the European aviation industry.

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CONTENTS

Contributing partners	3
Document Change Log	3
Approval status	3
Acronyms	4
Executive Summary	5
Description of Work	5
Problem Area	5
Results & Conclusions	5
Applicability	9
Contents	11
List of Figures	14
List of Tables	19
1 Introduction	20
1.1. Project context	20
1.2. Introduction to the Data4Safety programme	21
1.3. Research objective of Task 2.1	21
1.4. Definition of the directed study	22
1.5. Structure of the document	23
2 Methodology	24
2.1. Phase 1: Data selection and definitions	24
2.2. Phase 2: Analysis of ECR occurrence reports	25
2.3. Phase 3: Analysis of recorded flight data	26
2.4. Phase 4: Consolidation of results	27
2.5. Analytical structure common to both workstreams	27
3 Data selection and definitions	29
3.1. Description of data sources	29
3.1.1. ECR data	29
3.1.2. Recorded flight data	30
3.1.3. Exposure data	32
3.2. Definition of scope	34
3.2.1. Operational scope	34
3.2.2. Temporal scope	35
3.2.3. Geographical scope	35
3.2.4. Turbulence scope	36
3.2.5. Flight phase scope	36
3.2.6. D4S Data Governance conditions and scope of results	36
3.3. Definition of Safety Performance Indicators	37

4	Data processing and turbulence identification	40
4.1.	Identification of turbulence-related ECR occurrences	40
4.1.1.	Data selection and initial filtering	41
4.1.2.	Identification of turbulence events using structured occurrence data	41
4.1.3.	Narrative-based identification of turbulence events	42
4.1.4.	LLM-based occurrence validation	44
4.1.5.	Final event dataset	45
4.1.6.	Data quality improvements	46
4.2.	Identification of turbulence episodes in the recorded flight data	50
4.2.1.	Key definitions	50
4.2.2.	Data processing	51
4.2.3.	Bias correction in vertical accelerometer readings	53
4.2.4.	Identification of turbulent events using recorded flight data	54
4.2.5.	Calculation of intensity level	56
4.2.6.	Aggregation of turbulence events into episodes	58
4.2.7.	Identification of flight phase for turbulence episodes	59
5	Characterisation of turbulence encounters	61
5.1.	Preliminary considerations	61
5.1.1.	Data sources and their complementarity	61
5.1.2.	Treatment of very high severity outliers in the ECR dataset	62
5.2.	General characterisation and turbulence observation frequency	63
5.2.1.	Overall turbulence observation frequency	63
5.2.2.	Intensity level	66
5.2.3.	Physical structure of a turbulence episode	70
5.3.	Altitude and flight phase	73
5.3.1.	Flight phase	74
5.3.2.	Altitude	79
5.3.3.	Concentration of turbulent episodes at the end of cruise and the role of on-board weather radar technology	82
5.4.	Injuries	85
5.5.	Aircraft damage	95
5.6.	Turbulence type	98
5.7.	Route type	105
5.8.	Geographical distribution	107
5.9.	Seasonality	111
6	Analysis of consequential events and safety-barrier performance	117
6.1.	Consequential events in the ECR dataset	117
6.2.	Consequential events in the recorded flight data	119
6.2.1.	Methodology	120

6.2.2.	Results	122
6.3.	Analysis of safety barriers	131
6.3.1.	Bow tie safety risk assessment framework and ERCS alignment	132
6.3.2.	Barrier assessment results	136
6.3.3.	Escalation factors	139
7	Discussion of results	141
7.1.	Summary of main findings	141
7.2.	Limitations	149
7.2.1.	Turbulence-related ECR occurrences	149
7.2.2.	Recorded flight data	151
7.2.3.	Data Governance (DaGo) constraints	153
7.2.4.	Scope and results aggregation	153
7.2.5.	Exposure data	154
7.2.6.	Consequential events	155
7.2.7.	Bow tie analysis	155
8	Conclusions	157
8.1.	In-flight turbulence	157
8.2.	Conclusions on the cooperation with D4S in research studies	160
9	Recommendations	162
9.1.	Recommendations for future research	162
9.2.	Recommendation to airlines	166
9.3.	Recommendations on D4S capabilities for future research	166
10	References	167
Appendix A	Safety Performance Indicators	170
Appendix B	Detailed ECR Processing Logic	187
Appendix C	Additional analysis of recorded flight data	189
Appendix D	Additional analysis of consequential events and Safety barriers performance	197

LIST OF FIGURES

FIGURE 1 - HIGH-LEVEL OVERVIEW OF THE PROJECT STRUCTURE IN FOUR PHASES	24
FIGURE 2 - DISTRIBUTION OF FLIGHTS BY AIRCRAFT TYPE WITHIN THE RECORDED FLIGHT DATA	32
FIGURE 3 - BREAKDOWN OF ECR OCCURRENCES BY OPERATOR AND ROUTE TYPE	33
FIGURE 4 - COVERAGE ALIGNMENT BETWEEN EXPOSURE DATASETS AND ECR OCCURRENCES	34
FIGURE 5 - ROLE OF SPIS IN THE CHARACTERISATION AND ANALYSIS EXERCISE	37
FIGURE 6 - PROCESS FOR SPI GENERATION	38
FIGURE 7 - EVOLUTION OF THE VOLUME OF OCCURRENCES THROUGHOUT THE TURBULENCE IDENTIFICATION PIPELINE	46
FIGURE 8 - COMPLETENESS OF THE ECR ATTRIBUTES THAT UNDERWENT DATA QUALITY ENHANCEMENT	49
FIGURE 9 – OVERVIEW OF THE DATA PREPROCESSING AND IDENTIFICATION OF IN-FLIGHT TURBULENCE EVENTS USING RECORDED FLIGHT DATA	50
FIGURE 10 - NUMBER OF FLIGHTS AFTER EACH PREPROCESSING STEP OF THE RECORDED FLIGHT DATA.....	53
FIGURE 11 - ILLUSTRATION OF THE BIAS IN THE VERTICAL ACCELERATION PARAMETER FOR A FLIGHT. GREY BAND CORRESPONDS TO THE WINDOW IN WHICH FLIGHT IS CONSIDERED STABLE	54
FIGURE 12 - TYPICAL BEHAVIOUR IN THE VERTICAL ACCELERATION PARAMETER (N_z) IN TWO DIFFERENT SCENARIOS: MANOEUVRE (FLIGHT #1), AND TURBULENCE (FLIGHT #2)	56
FIGURE 13 - ILLUSTRATION OF TWO INITIAL CRITERIA EVALUATED FOR DETERMINING THE START AND END OF TURBULENCE EVENTS	58
FIGURE 14 - ILLUSTRATION OF VARIOUS TURBULENCE EVENTS, SEPARATED BY A DIFFERENCE IN TIME Δt	59
FIGURE 15 - EVOLUTION OF TOTAL AND TURBULENCE-RELATED ECR OCCURRENCES PER 1,000 FLIGHTS	64
FIGURE 16 - EVOLUTION OF THE SHARE OF TURBULENCE-RELATED OCCURRENCES TO TOTAL VOLUME OF ECR OCCURRENCES ..	64
FIGURE 17 - PERCENTAGE OF FLIGHTS WITH AND WITHOUT TURBULENCE (RECORDED FLIGHT DATA).....	65
FIGURE 18 - DISTRIBUTION OF FLIGHTS BY NUMBER OF TURBULENCE EPISODES PER FLIGHT (N), AS A PERCENTAGE (RECORDED FLIGHT DATA)	66
FIGURE 19 - SHARE OF TURBULENCE-RELATED ECR OCCURRENCES BY INTENSITY LEVEL	66
FIGURE 20 - BREAKDOWN OF TURBULENCE EPISODES BY INTENSITY LEVEL (RECORDED FLIGHT DATA)	67
FIGURE 21 - EVOLUTION OF FREQUENCY OF TURBULENCE-RELATED ECR OCCURRENCES, PER 1,000 FLIGHTS, BY INTENSITY LEVEL	68
FIGURE 22 - EVOLUTION OF THE DISTRIBUTION OF TURBULENCE-RELATED ECR OCCURRENCES BY INTENSITY LEVEL (ONLY CLASSIFIED INTENSITY LEVELS, EXCLUDING “NOT REPORTED”)	70
FIGURE 23 - AVERAGE EPISODE DURATION BY INTENSITY (RECORDED FLIGHT DATA)	71
FIGURE 24 - AVERAGE NUMBER OF EVENTS PER EPISODE BY INTENSITY (RECORDED FLIGHT DATA)	71
FIGURE 25 - AVERAGE EPISODE DURATION BY FLIGHT PHASE AND INTENSITY LEVEL (RECORDED FLIGHT DATA)	72
FIGURE 26 - PROBABILITY DENSITY OF THE AVERAGE EPISODE OSCILLATION FREQUENCY BY INTENSITY (RECORDED FLIGHT DATA)	72
FIGURE 27 - PROBABILITY DENSITY OF EPISODE DURATION BY INTENSITY	73
FIGURE 28 - BREAKDOWN OF TURBULENCE EPISODES BY FLIGHT PHASE (RECORDED FLIGHT DATA)	74
FIGURE 29 - AVERAGE FLIGHT PHASE DURATION, IN MINUTES (RECORDED FLIGHT DATA)	75

FIGURE 30 - DISTRIBUTION OF TURBULENCE EPISODES BY FLIGHT PHASE, NORMALISED BY 1,000 FLIGHT MINUTES WITHIN EACH PHASE (RECORDED FLIGHT DATA).....	76
FIGURE 31 - DISTRIBUTION OF TURBULENCE-RELATED ECR OCCURRENCES BY FLIGHT PHASE	77
FIGURE 32 - DISTRIBUTION OF TURBULENCE-RELATED ECR OCCURRENCES OF KNOWN INTENSITY LEVEL BY FLIGHT PHASE AND INTENSITY LEVEL.....	78
FIGURE 33 - DISTRIBUTION OF TURBULENCE EPISODES BY ALTITUDE AND FLIGHT PHASE (RECORDED FLIGHT DATA, BIN SIZE = 1,000 FT).....	80
FIGURE 34 - PROBABILITY DENSITY OF ALTITUDE DISTRIBUTION BY INTENSITY LEVEL (RECORDED FLIGHT DATA).....	81
FIGURE 35 - DISTRIBUTION OF TURBULENCE-RELATED ECR OCCURRENCES BY ALTITUDE (FL) AND INTENSITY LEVEL.....	82
FIGURE 36 - PROBABILITY DENSITY OF TURBULENCE EPISODES WITH RESPECT TO PHASE PROGRESS, BY FLIGHT PHASE (RECORDED FLIGHT DATA).....	83
FIGURE 37 - PROBABILITY DENSITY OF TURBULENCE EPISODES WITH RESPECT TO CRUISE PROGRESS, BY AIRCRAFT TYPE (LEFT = NEWER GENERATION MODELS, RIGHT = OLDER GENERATION MODELS). RED DASHED LINE MARKS LAST 10% OF CRUISE PHASE	85
FIGURE 38 - DISTRIBUTION OF TURBULENCE-RELATED ECR OCCURRENCES BY INJURY SEVERITY	86
FIGURE 39 - EVOLUTION OF FREQUENCY OF TURBULENCE-RELATED OCCURRENCES PER 1,000 FLIGHTS, BY INJURY SEVERITY LEVEL	87
FIGURE 40 - DISTRIBUTION OF TURBULENCE-RELATED OCCURRENCES WITH INJURIES BY INTENSITY LEVEL AND INJURY SEVERITY LEVEL	88
FIGURE 41 - DISTRIBUTION OF TURBULENCE-RELATED ECR OCCURRENCES BY FLIGHT PHASE AND INJURY SEVERITY LEVEL	89
FIGURE 42 - DISTRIBUTION OF INJURIES IN TURBULENCE-RELATED ECR OCCURRENCES BY AFFECTED TYPE OF PERSON.....	90
FIGURE 43 - DISTRIBUTION OF TURBULENCE-RELATED ECR OCCURRENCES BY INJURY SEVERITY LEVEL AND AFFECTED TYPE OF PERSON (ONLY KNOWN INFORMATION).....	90
FIGURE 44 - DISTRIBUTION OF TURBULENCE-RELATED ECR OCCURRENCES WITH INJURY BY ACTIVITY DURING INJURY	91
FIGURE 45 - DISTRIBUTION OF INJURIES AMONGST CABIN CREW BY ACTIVITY DURING INJURY AND INJURY SEVERITY LEVEL	92
FIGURE 46 - DISTRIBUTION OF INJURIES AMONGST PASSENGERS BY ACTIVITY AND INJURY SEVERITY LEVEL	92
FIGURE 47 - DISTRIBUTION OF TURBULENCE-RELATED OCCURRENCES BY INJURY LOCATION	93
FIGURE 48 - EVOLUTION OF THE DISTRIBUTION OF INJURIES IN TURBULENCE-RELATED ECR OCCURRENCES BY INJURY LOCATION, WHEN INJURY LOCATION IS KNOWN ("NOT REPORTED" LOCATION IS EXCLUDED)	94
FIGURE 49 - DISTRIBUTION OF INJURIES AFFECTING CABIN CREW IN TURBULENCE-RELATED OCCURRENCES BY INJURY LOCATION AND INJURY SEVERITY LEVEL	95
FIGURE 50 - DISTRIBUTION OF INJURIES AFFECTING PASSENGERS IN TURBULENCE-RELATED OCCURRENCES BY INJURY LOCATION AND INJURY SEVERITY LEVEL	95
FIGURE 51 - DISTRIBUTION OF TURBULENCE-RELATED ECR OCCURRENCES BY DAMAGE SEVERITY LEVEL	96
FIGURE 52 - DISTRIBUTION OF OCCURRENCES WITH MINOR AND SUBSTANTIAL DAMAGE SEVERITY LEVEL BY INTENSITY LEVEL ...	97
FIGURE 53 - EVOLUTION OF THE DISTRIBUTION OF TURBULENCE-RELATED OCCURRENCES BY KNOWN DAMAGE SEVERITY LEVEL (ALL OCCURRENCES INCLUDED)	98
FIGURE 54 - BREAKDOWN OF TURBULENCE-RELATED ECR OCCURRENCES BY TURBULENCE TYPE	99

FIGURE 55 - EVOLUTION OF THE DISTRIBUTION OF TURBULENCE-RELATED OCCURRENCES WITH KNOWN TURBULENCE TYPE BY TURBULENCE TYPE	100
FIGURE 56 - PERCENTAGE OF TURBULENCE-RELATED ECR OCCURRENCES WITH AND WITHOUT INJURIES BY TURBULENCE TYPE	100
FIGURE 57 - DISTRIBUTION OF TURBULENCE-RELATED ECR OCCURRENCES WITH INJURIES OF KNOWN SEVERITY LEVEL AND KNOWN TURBULENCE TYPE	101
FIGURE 58 - DISTRIBUTION OF TURBULENCE-RELATED ECR OCCURRENCES BY ALTITUDE (FLIGHT LEVEL) AND TURBULENCE TYPE	102
FIGURE 59 - DISTRIBUTION OF TURBULENCE-RELATED OCCURRENCES BY FLIGHT PHASE AND TURBULENCE TYPE	103
FIGURE 60 - DISTRIBUTION OF TURBULENCE-RELATED ECR OCCURRENCES BY TURBULENCE TYPE AND INTENSITY LEVEL	103
FIGURE 61 - DISTRIBUTION OF TURBULENCE-RELATED ECR OCCURRENCES BY ROUTE TYPE	106
FIGURE 62 - DISTRIBUTION OF TURBULENCE-RELATED ECR OCCURRENCES BY ROUTE TYPE AND TURBULENCE TYPE.....	106
FIGURE 63 - DISTRIBUTION OF TURBULENCE-RELATED ECR OCCURRENCES BY ROUTE TYPE AND INTENSITY LEVEL	107
FIGURE 64 - DISTRIBUTION OF TURBULENCE-RELATED ECR OCCURRENCES BY ROUTE TYPE AND INJURY SEVERITY LEVEL.....	107
FIGURE 65 - DISTRIBUTION OF TURBULENCE-RELATED ECR OCCURRENCES BY STATE AREA OF OCCURRENCE, NORMALISED PER 1,000 ECR OCCURRENCES PER STATE	108
FIGURE 66 - GEOGRAPHICAL DISTRIBUTION OF CLEAR-AIR TURBULENCE (CAT) OCCURRENCES (ECR)	109
FIGURE 67 - GEOGRAPHICAL DISTRIBUTION OF CONVECTIVE TURBULENCE OCCURRENCES (ECR).....	109
FIGURE 68 - DISTRIBUTION OF TURBULENCE EPISODES BY H3 INDEX, NORMALISED PER 1,000 FLIGHTS (RECORDED FLIGHT DATA)	110
FIGURE 69 - DISTRIBUTION OF MODERATE AND SEVERE TURBULENCE EPISODES DURING CRUISE BY H3 INDEX, NORMALISED PER 1,000 FLIGHTS. NORMALISATION IS PERFORMED BASED ON TOTAL NUMBER OF FLIGHTS WITHIN EACH H3 INDEX.....	111
FIGURE 70 - SEASONALITY OF FREQUENCY OF TURBULENCE-RELATED ECR OCCURRENCES (TOTAL AND WITH INJURIES). NOTE THE DUAL VERTICAL AXIS	112
FIGURE 71 - SEASONALITY OF TURBULENCE-RELATED ECR OCCURRENCES BY TURBULENCE TYPE	113
FIGURE 72 - SEASONALITY OF TURBULENCE-RELATED ECR OCCURRENCES BY TURBULENCE TYPE, PER 1,000 FLIGHTS	113
FIGURE 73 - SEASONALITY OF TURBULENCE-RELATED ECR OCCURRENCES BY INTENSITY LEVEL, PER 1,000 FLIGHTS.....	114
FIGURE 74 - SEASONAL DISTRIBUTION OF TURBULENCE EPISODES PER 1,000 FLIGHTS (RECORDED FLIGHT DATA).....	114
FIGURE 75 - SEASONAL DISTRIBUTION OF TURBULENCE EPISODES OF LIGHT INTENSITY PER 1,000 FLIGHTS.....	115
FIGURE 76 - SEASONAL DISTRIBUTION OF TURBULENCE EPISODES OF MODERATE INTENSITY PER 1,000 FLIGHTS (RECORDED FLIGHT DATA).....	115
FIGURE 77 - SEASONAL DISTRIBUTION OF TURBULENCE EPISODES OF SEVERE INTENSITY PER 1,000 FLIGHTS (RECORDED FLIGHT DATA).....	116
FIGURE 78 - CONSEQUENTIAL EVENTS OF TURBULENCE-RELATED ECR OCCURRENCES	119
FIGURE 79 - RATE OF CONSEQUENTIAL EVENTS PER 1,000 TURBULENCE EPISODES, BY INTENSITY LEVEL (LOGARITHMIC SCALE)	124
FIGURE 80 - RATE OF CONSEQUENTIAL EVENTS BY 1,000 TURBULENCE EPISODES. VERTICAL BARS SHOW RATES OF COMBINED CONSEQUENTIAL EVENTS, BARS ON THE LEFT SHOW AGGREGATED RATES PER CONSEQUENTIAL TYPE	125
FIGURE 81 - BREAKDOWN OF AUTOPILOT DISENGAGEMENTS BY FLIGHT PHASE	126

FIGURE 82 - BREAKDOWN OF AUTOPILOT DISENGAGEMENTS BY NUMBER OF DISCONNECTIONS	127
FIGURE 83 - BREAKDOWN OF OVERSPEED EVENTS BY FLIGHT PHASE	127
FIGURE 84 - PROBABILITY DENSITY OF AVERAGE MACH IN THE MINUTE PRECEDING EPISODES, AVERAGE MACH DURING OVERSPEED EVENTS, AND MAXIMUM MACH DURING OVERSPEED EPISODES, BY INTENSITY LEVEL (LIGHT AND MODERATE+SEVERE) ..	128
FIGURE 85 - PROBABILITY DENSITY OF THE INCREASE IN CALIBRATED AIRSPEED (CAS) AND MACH NUMBER DURING OVERSPEED EVENTS	129
FIGURE 86 – TYPES OF AIRCRAFT UPSET. VERTICAL BARS SHOW NUMBER OF UPSETS CAUSED BY EACH COMBINATION OF ATTITUDE EXCURSION. LATERAL BARS SHOW TOTAL NUMBER OF UPSETS BY TYPE OF AIRCRAFT UPSET	129
FIGURE 87 - BREAKDOWN OF AIRCRAFT UPSET BY FLIGHT PHASE	130
FIGURE 88 - PROBABILITY DENSITY OF THE MINIMUM AND MAXIMUM Nz VALUE BY INTENSITY. VERTICAL LINES SHOW THE FOUR HIGH LOAD THRESHOLDS	131
FIGURE 89 - AVERAGE TIME BELOW (LEFT) AND ABOVE (RIGHT) THE LOAD THRESHOLDS FOR EPISODES THAT EXCEEDED THEM AT SOME POINT [s]	131
FIGURE 90 - BOW TIE FRAMEWORK APPLIED TO TURBULENCE ENCOUNTERS	132
FIGURE 91 - AGGREGATED ASSESSMENT OF THE ERCS BARRIERS TYPES IN THE TURBULENCE-RELATED ECR OCCURRENCES ..	137
FIGURE 92 - ESCALATION FACTORS IDENTIFIED IN THE TURBULENCE-RELATED ECR OCCURRENCES	140
FIGURE 93 - PROBABILITY DENSITY OF EPISODE DURATION BY FLIGHT PHASE	190
FIGURE 94 - PROBABILITY DENSITY OF Nz RANGE BY INTENSITY	191
FIGURE 95 - PROBABILITY DENSITY OF Nz RANGE BY FLIGHT PHASE	191
FIGURE 96 - PROBABILITY DENSITY OF THE AVERAGE Nz SIGNAL VALUE BY INTENSITY.....	192
FIGURE 97 - PROBABILITY DENSITY OF THE MINIMUM AND MAXIMUM Nz SIGNAL VALUE BY INTENSITY	192
FIGURE 98 - PROBABILITY DENSITY OF THE AVERAGE Nz SIGNAL VALUE BY FLIGHT PHASE	192
FIGURE 99 - PROBABILITY DENSITY OF THE MINIMUM AND MAXIMUM Nz SIGNAL VALUE BY FLIGHT PHASE.....	192
FIGURE 100 - AVERAGE NUMBER OF OSCILLATIONS PER EPISODE BY INTENSITY	193
FIGURE 101 - AVERAGE NUMBER OF EVENTS PER EPISODE BY FLIGHT PHASE	193
FIGURE 102 - AVERAGE NUMBER OF EVENTS PER EPISODE BY FLIGHT PHASE AND INTENSITY	194
FIGURE 103 - PROBABILITY DENSITY OF TURBULENCE EPISODES OF MODERATE INTENSITY WITH RESPECT TO PHASE PROGRESS, BY FLIGHT PHASE	196
FIGURE 104 - PROBABILITY DENSITY OF TURBULENCE EPISODES OF SEVERE INTENSITY WITH RESPECT TO PHASE PROGRESS, BY FLIGHT PHASE	196
FIGURE 105 - OPERATIONAL CONSEQUENCES IDENTIFIED THROUGH ECR	198
FIGURE 106 - NUMBER OF AUTOPILOT DISENGAGEMENTS EVENTS BY INTENSITY.....	199
FIGURE 107 - NUMBER OF AUTOPILOT DISENGAGEMENTS EVENTS BY INTENSITY, NORMALISED BY 1,000 TURBULENCE EPISODES. NORMALISATION IS BASED ON TOTAL NUMBER OF TURBULENCE EPISODES WITHIN EACH INTENSITY	199
FIGURE 108 - AVERAGE NUMBER OF AUTOPILOT DISENGAGEMENTS BY INTENSITY	199
FIGURE 109 - NUMBER OF OVERSPEED EVENTS BY INTENSITY	200
FIGURE 110 - NUMBER OF OVERSPEED EVENTS BY INTENSITY, NORMALISED BY 1,000 TURBULENCE EPISODES. NORMALISATION IS BASED ON TOTAL NUMBER OF TURBULENCE EPISODES WITHIN EACH INTENSITY	200
FIGURE 111 - NUMBER OF AIRCRAFT UPSET EVENTS BY INTENSITY	201

FIGURE 112 - NUMBER OF AIRCRAFT UPSET EVENTS BY INTENSITY, NORMALISED BY 1,000 TURBULENCE EPISODES.....201

FIGURE 113 - NUMBER OF TCAS RA EVENTS BY INTENSITY202

FIGURE 114 - NUMBER OF TCAS RA EVENTS BY INTENSITY, NORMALISED BY 1,000 TURBULENCE EPISODES.....202

FIGURE 115 - BREAKDOWN OF TCAS RA EVENTS BY FLIGHT PHASE202

FIGURE 116 - BARRIER TYPE 1 ACTIONS, ASSESSED EFFECTIVENESS AND LINKED CONSEQUENTIAL EVENTS206

FIGURE 117 - BARRIER TYPE 2 ACTIONS, ASSESSED EFFECTIVENESS AND LINKED CONSEQUENTIAL EVENTS207

FIGURE 118 - BARRIER TYPE 3 ACTIONS, ASSESSED EFFECTIVENESS AND LINKED CONSEQUENTIAL EVENTS209

FIGURE 119 - BARRIER TYPE 4 ACTIONS, ASSESSED EFFECTIVENESS AND LINKED CONSEQUENTIAL EVENTS210

FIGURE 120 - BARRIER TYPE 5 ACTIONS, ASSESSED EFFECTIVENESS AND LINKED CONSEQUENTIAL EVENTS211

FIGURE 121 - BARRIER TYPE 6 ACTIONS, ASSESSED EFFECTIVENESS AND LINKED CONSEQUENTIAL EVENTS212

LIST OF TABLES

TABLE 1 - ANALYTICAL STRUCTURE OF THE ECR AND FLIGHT DATA WORKSTREAMS BY PHASE STEP	27
TABLE 2 - MANUAL VALIDATION OF THE LLM-BASED OCCURRENCE CLASSIFICATION	45
TABLE 3 - SUMMARY OF THE SOURCE OF THE BUSINESS RULES APPLIED TO EACH ATTRIBUTE	47
TABLE 4 - RMS OF VERTICAL ACCELERATION BOUNDS FOR CATEGORISING TURBULENCE INTENSITIES	57
TABLE 5 – FLIGHT PHASE CLASSIFICATION CRITERIA APPLIED TO TURBULENCE EPISODES	59
TABLE 6 - DETAILS OF THE IDENTIFIED VERY HIGH SEVERITY ECR OCCURRENCES	62
TABLE 7 - GENERAL FREQUENCY OF TURBULENCE EPISODES IN THE RECORDED FLIGHT DATA	65
TABLE 8 – FREQUENCY OF TURBULENCE EPISODES BY INTENSITY LEVEL, PER 1,000 FLIGHTS (RECORDED FLIGHT DATA)	68
TABLE 9 - CHARACTERISATION OF THE AVERAGE TURBULENCE EPISODE	71
TABLE 10 - CONSEQUENTIAL EVENT GROUPS USED IN THE ASSESSMENT	117
TABLE 11 – MMO AND VMO VALUES BY AIRCRAFT FAMILY [32]	121
TABLE 12 – BOUNDS FOR THE DEFINITION OF AIRCRAFT UPSET AND ONSET OF AIRCRAFT UPSET	121
TABLE 13 – BOUNDS FOR THE DEFINITION OF HIGH LOAD CONSEQUENTIAL EVENTS	122
TABLE 14 - PRINCIPAL BOW TIE COMPONENTS USED IN THE TURBULENCE ASSESSMENT	132
TABLE 15 - ERCS ASSESSMENT CATEGORIES TO CLASSIFY BARRIER EFFECTIVENESS	135
TABLE 16 - BARRIER ACTIONS IDENTIFIED IN TURBULENCE-RELATED ECR OCCURRENCES	203

1 INTRODUCTION

1.1. Project context

The project “Advanced systems and soLutions for Better practices Against hazarDs in the AviatiOn System”, hereinafter referred to as ‘ALBATROS’, is initiated as a Horizon Europe funded project to maintain a high level of safety and resilience in the new environment that the international aviation sector encounters. This section introduces the new challenges and the rationale behind the ALBATROS project.

The overall ambition of the ALBATROS project is to improve the resilience of aircraft and airports to emerging hazards (weather, new technologies, denser traffic, cyber security, etc.) whilst increasing survivability of passengers, crew and aviation-related work force such as ground handlers and emergency personnel. This includes aircraft currently in service as well as future zero emissions aircraft using new fuels and higher power or novel electrical energy systems.

In the upcoming decades the aviation industry will face some extensive challenges. On the one hand it needs to accommodate a significant growth in demand while maintaining safety, security, punctuality and economic viability. On the other hand, there are challenges related to climate change, emergence of new technologies, geo-political disruptions, and reducing the emission of greenhouse gasses of the whole aviation supply chain. With all these challenges, safety and resilience are the primary concern for the global transport systems. Resilience should be built into transport systems to prevent, mitigate and recover from disruptions and potential hazards to enhance safety. The European Union has set ambitious targets for its sustainable and smart mobility strategy which must be addressed with innovation activities that must reinforce three safety pillars: technologies, regulations and human factors. Fundamental and crucial changes to the air transport system within the EU are underway to reduce emissions to create a climate friendly sustainable future with zero emissions.

Ambitious milestones have been set for the aviation sector: climate neutral airports and zero-emission large aircraft market ready by 2035 and a 90% cut in aircraft emissions by 2050.¹ To achieve these targets, the aviation industry is investigating new technologies which radically emerged. These technologies mostly rely on the use of new fuels such as hydrogen and new propulsion systems, both of which will require new electrical high-power architectures both in aircraft and in equipment and ground handling vehicles such as tow tractors and charging units at airports. The hazards and challenges that are created by these evolutions must be properly assessed. Mitigation plans must be defined which consider human factors and the use of appropriate innovative technologies to maintain resilience and reinforce decision making approaches. Especially in crisis situations such as in-flight emergencies, commercial flight incidents or accidents, or events that cause serious Air Traffic Management (ATM) disruptions. Europe’s aviation safety record is already very high compared to the rest of the world, notably due to European Union Aviation Safety Agency (EASA) regulations and State oversight assisted by the implementation of key initiatives such as the

¹ https://climate.ec.europa.eu/eu-action/transport/reducing-emissions-aviation_en

European Aviation Crisis Coordination Cell (EACCC), the International Civil Aviation Organization (ICAO) Global Aeronautical Distress & Safety System (GADSS), and safety analysis capabilities such as Data4Safety (D4S). EASA oversees the right implementation of these policies and networks, while industry associations like the Airports Council International (ACI)-Europe also supports these means.

The effects of climate change create uncertainty for the future of aviation [1]. They are becoming more apparent as meteorological conditions are moving away from usual patterns. In some locations this might lead to more frequent extreme weather conditions, e.g. such as flooding and occurrences of severe storm systems. The different facets of the aviation sector, which are strongly influenced by the weather, have always needed to adapt themselves by developing new technology to deal with weather hazards, either on the aircraft such as on-board weather radars and icing protection, or at airports with sophisticated ground measuring instrumentation to detect potential threats such as wind shear. En-route, aircraft also receive updated weather data, especially when changes to predicted weather require changes to routing. In addition, abnormal weather conditions can have a negative effect on Air Traffic Control (ATC) capacity causing delays to scheduled flights and passenger travel.

Another important aspect which must be considered is technical advancement in the new digital age. With the ongoing digitalization of aviation systems, new risks may occur. Especially, cyber security is considered a new type of threat within the aviation sector, which challenges the seamlessly interconnected air transport system, which relies on more digital data and communication both in their development and operation. Therefore, it is necessary to prepare the aviation industry for this threat.

1.2. Introduction to the Data4Safety programme

Data4Safety (D4S) is a data collection and data analysis programme for management of safety risks at European level. Data4Safety was established in partnership with EASA, airlines, manufacturers, ANSPs, authorities, airports, etc. Over the last few years, EASA coordinated the establishment of the Data4Safety programme with the aim to better know where the risks are (identification of safety issues), to determine the nature of these risks (risk assessment) and to verify if safety actions are delivering the needed level of safety (safety performance monitoring).

EASA is coordinating the availability of D4S as common digital platform and aviation data space to external organisations (in full compliance with the D4S principles, data protection and agreed Data Governance), including for the ALBATROS project.

1.3. Research objective of Task 2.1

As weather hazards are becoming more serious and frequent due to climate change, and other hazards are emerging through the gradual introduction of new technology, there is a need to reassess current aircraft operating practices and infrastructure (e.g. airports) to ensure that the appropriate level of resilience exists to ensure that current safety levels can be continuously improved. Introduction of new technologies in

aviation (like hydrogen fuelled aircraft), new operations (such as Urban Air Mobility) and future challenges due to climate change (such as increased turbulence) will result in new risks.

One of the ALBATROS project objectives is to develop safety risk models and analyse safety data to predict and prevent emerging and future hazards in aviation. Specifically, Task 2.1 focuses on assessing the risks associated with new hazards in aviation and new aircraft entrants using a scenario-based risk assessment approach, which combines modelling, expert judgement, and safety data analysis to provide a comprehensive risk assessment.

This report serves as an annex to the Task 2.1 deliverable (D2.1) and presents the methodology and findings of a directed study on in-flight turbulence, which was conducted as part of Task 2.1 using the Data4Safety programme.

1.4. Definition of the directed study

The ALBATROS project utilised the D4S programme to conduct a directed study on in-flight turbulence, leveraging available datasets and analytical capabilities of D4S to examine the impact of turbulence encounters on flight safety and flight operations. Turbulence encounters are expected to increase in likelihood and intensity over the next decades as a results of climate change. The directed study, which analysed occurrence reports, flight data, and traffic data (made available through Data4Safety), aimed to provide contextual data on future turbulence risk, demonstrate the utility of D4S, and offer guidance on data-driven safety analytics in aviation. By focusing on in-flight turbulence during climb, cruise, and descent phases, the study established a baseline turbulence risk assessment, providing valuable insights into current risks and future challenges. Note that ALBATROS Task 2.3 addresses the effect of climate change on airport operations, including take-off and final approach/landing operations.

1.5. Structure of the document

The report has the following sections:

- Chapter 2 presents the methodology of the study, including a detailed description of the key phases of the project and the phases carried out within them. The following chapters are aligned with the presented methodology.
- Chapter 3 describes the initial phase (Data selection and definitions), where the scope of the study is outlined, in addition to a detailed description of the various data sources and the definition of the Safety Performance Indicators (SPIs).
- Chapter 4 presents the data processing and the identification methodology used to identify turbulence-related occurrences in the ECR data and turbulence episodes in the recorded flight data.
- Chapters 5 and 6 present the main findings of the study, the former related to the characterisation of turbulence encounters and the latter to the analysis of consequential events and safety barrier performance.
- Chapter 7 presents the discussion of the results, including a summary of the main findings and the limitations of the study.
- Chapter 8 presents the conclusions of the study, including those related to in-flight turbulence and those related to the capabilities and use of the D4S programme to support research.
- Finally, Chapter 9 presents a set of recommendations for future research on turbulence, the use of the approach and results of the study by airlines, and leveraging the D4S capabilities in new research studies.

2 METHODOLOGY

The present study aims to characterise and analyse in-flight turbulence during the climb, cruise, and descent phases of Commercial Air Transport operations involving Complex Aircraft, using the data and analytical capabilities provided by the Data4Safety programme. The study seeks to identify significant observations regarding turbulence occurrences and to explore the potential of these data sources for turbulence identification and analysis. The resulting visualisations, findings, and observations are intended to provide objective evidence that may support future research and future risk assessments of turbulence events. This chapter describes the methodology used to achieve those objectives.

The analytical approach is built around two data sources, namely:

1. Safety occurrence reports data from the **European Central Repository (ECR)**; and
2. Operational, **recorded in-flight data** from a large Flight Data Monitoring (FDM) dataset.

Both datasets are assets of the D4S programme and form the backbone for the study of in-flight turbulence in the present study. Each data source is analysed through a dedicated workstream and contributes to specific and additional insights into turbulence events. The first workstream uses ECR data to assess turbulence events on the basis of safety reports submitted following occurrences (incidents and accidents) involving in-flight turbulence encounters. The second workstream uses recorded flight data to quantify the frequency and intensity of turbulence encounters directly identified in operational flight data recordings. Both data sources are described in detail in Chapter 3.

The overall methodology is organised into four sequential phases, illustrated in Figure 1 and listed below:

1. Data selection and definitions
2. Analysis of ECR occurrence reports
3. Analysis of recorded flight data
4. Consolidation of results

Each phase is described in detail hereinafter.



Figure 1 - High-level overview of the project structure in four phases

2.1. Phase 1: Data selection and definitions

The first phase establishes the analytical foundations of the study. Its primary output is a fully specified and agreed analytical framework that governs the ECR and recorded flight data analyses conducted in Phases 2 and 3. This phase begins with the consolidation and refinement of the project scope, including the definition

of study boundaries and the agreement of a high-level methodology across project stakeholders. This coordination ensures that the two workstreams are aligned from the outset and that the analytical approach is feasible given the available data and programme capabilities.

The set of Safety Performance Indicators (SPIs) is defined for both workstreams during this phase. Details on the SPI definition can be found in Chapter 3.3. These specifications are converted into algorithmic specifications: high-level pseudocodes that describe precisely how each indicator will be computed from the underlying data. Pseudocodes have been reviewed and consolidated across stakeholders prior to their implementation.

2.2. Phase 2: Analysis of ECR occurrence reports

The second phase applies the framework defined for the analysis of the ECR data developed in Phase 1 of the project. Its objective is to identify, characterise, and quantify in-flight turbulence encounters based on aviation safety occurrence data recorded in the ECR. The ECR collects reports provided by airlines, ANSPs, NAAs, among other stakeholders. The reports encode the information related to the safety occurrence using the ECCAIRS2 taxonomy [3], which defines a set of structured attributes and the values that can be allocated by the reporting entity to the occurrence report. Some of the attributes defined by the taxonomy may be structured (e.g., the permitted values may only be numeric or have a limited set of possible labels to choose from), while others may be free-text (to provide the reporter freedom to provide information regarding the occurrence through the use of natural language).

Several tasks are carried out during this phase:

- **Identification of turbulence occurrences.** Occurrences related to in-flight turbulence encounters are extracted from the ECR database using two complementary techniques. The first consists of a traditional search based on structured attributes from the ECCAIRS2 taxonomy, where occurrences are classified as turbulence-related based on the presence of specific values indicating turbulence involvement for specific structured attributes. The second technique consists of exploiting specific free-text attributes which contain narratives of the occurrence, where specific keywords related to turbulence are searched for which may be indicative of turbulence being relevant for that occurrence. These two approaches are then complemented by an AI-based analysis of these narrative attributes, where natural language analytical techniques and Large Language Models (LLMs) are applied to understand the context of the occurrence and to validate that turbulence played a significant role in the safety event. These models serve an additional objective: extracting event information that would otherwise be unavailable in the structured taxonomy for further analysis.
- **Characterisation of turbulence occurrences.** The identified occurrences are characterised against the SPIs defined in Phase 1, using both structured record attributes and AI-extracted characteristics where applicable.

- **Quantification of frequency and risk exposure.** Occurrence counts are computed and normalised using an exposure dataset (see Chapter 3.1.33.1.3), producing metrics normalised per flight that enable the assessment of the turbulence events on an exposure-adjusted basis.
- **Analysis of consequential events and safety barriers.** A bow tie framework is used as a structured means to define the safety barriers intended to prevent turbulence encounters, the adverse operational or safety outcomes a turbulence event may escalate into, which are referred to as consequential events, and the safety barriers that may prevent such an escalation. The ECR data is analysed using the taxonomy fields and the extracted information to characterise the barriers involved in each recorded occurrence and, where these barriers were ineffective or absent, to identify the consequential events resulting from the turbulence encounter.

2.3. Phase 3: Analysis of recorded flight data

The third phase aims to identify and analyse turbulence encounters in the recorded flight data. Unlike the ECR workstream, which relies on reported occurrences and subjective assessment of turbulence events, the analysis of flight data draws on continuous flight parameters recordings and captures objective data on turbulence encounters, regardless of whether they were formally reported. The phase comprises two main components: the detection of turbulence events in the flight data, and their subsequent characterisation.

The tasks carried out during Phase 3 are listed below:

- **Detection of turbulence events.** A dedicated algorithm is developed to identify turbulence encounters from recorded flight data using load factor peaks derived from aircraft accelerometer readings. The algorithm is designed to leverage parameters already decoded within the D4S programme and to process the available dataset of over 5.5 million flights. It incorporates four core steps:
 - Bias correction of accelerometer values to remove systematic offsets;
 - Identification of turbulent events based on load factor (normal acceleration) peaks exceeding defined thresholds;
 - Differentiation between load factor peaks caused by turbulence and those resulting from aircraft manoeuvres;
 - Consolidation of multiple turbulence events into distinct turbulence episodes.

The algorithm is subsequently applied to the recorded flight data to produce the turbulence encounter data used in the downstream analysis.

- **Characterisation, exposure, and consequential events.** The detected turbulence encounters are characterised using the SPIs defined in Phase 1, covering parameters including airspeed, altitude, geographical location, turbulence intensity, and flight phase, among others. Exposure metrics are computed on a per-flight basis, drawing directly on the flight counts available within the recorded flight data. The recorded flight data is additionally used to analyse consequential events aligned

with bow tie framework developed in Phase 2, with the objective of complementing and, where the data permits, extending the findings of the ECR-based analysis of consequential events.

2.4. Phase 4: Consolidation of results

The fourth phase integrates the outputs of the two analytical workstreams. Where the structure of the underlying datasets permits, results from the ECR and recorded flight data analyses are compared to identify consistent findings and to assess the degree to which the two workstreams corroborate one another. The scope for direct comparison is inherently constrained by the differences in data origin, coverage, and collection mechanism described in Chapter 3. This comparison is therefore conducted with appropriate care, and cross-workstream conclusions are drawn only where the evidence from both sources is sufficiently aligned.

2.5. Analytical structure common to both workstreams

Despite differences in data origin and analytical techniques, Phase 2 (ECR) and Phase 3 (recorded flight data) share the same underlying logical structure. A brief examination of this structure provides essential context for the results presented in Chapters 5 and 6.

In both workstreams, the analysis progresses through three sequential steps:

- 1. Identification of turbulence events;
- 2. Characterisation of the identified events; and
- 3. Analysis of consequential events.

The distinction between the two workstreams lies not in the structure of the analysis, but in how each step is implemented as a consequence of the fundamentally different nature of the underlying data. Table 1 summarises this structure and the difference between the two workstreams.

Table 1 - Analytical structure of the ECR and flight data workstreams by phase step

Data source	Identification	Characterisation	Consequential events
ECR occurrence reports	Structured queries, keyword search, LLM-based analysis	SPIs	Bow tie framework + SPIs
Recorded flight data	Ad-hoc turbulence identification algorithm	SPIs	SPIs

The identification step is where the two workstreams differ because of the nature of their respective data sources. In the ECR workstream, turbulence events must be extracted from a repository of safety occurrences using a combination of structured queries, keyword search, and AI-based analysis of narrative

report content. In the flight data workstream, turbulence events are identified directly from flight parameter recordings using dedicated algorithms applied to accelerometer data. The identification methods for both workstreams are described in detail in Chapter 4.

Once turbulence events have been identified, characterisation follows a common approach in both workstreams. SPIs provide a consistent and structured basis for quantifying and describing turbulence encounters, enabling comparable aspects of the ECR data and recorded flight data to be examined through a shared analytical framework. The definition and derivation of the SPIs are described in Section 3.3, and the characterisation results are presented in Chapter 5.

The third step examines the consequential events associated with the identified turbulence encounters. In the ECR workstream, the bow tie framework, supported by SPIs, structures the assessment of consequences and the relevant preventive and mitigating barriers. In the flight data workstream, consequence-related SPIs derived from recorded flight parameters are used to quantify directly observable operational outcomes. The results based on recorded flight data therefore provide operational evidence that complements and, where appropriate, corroborates the ECR safety assessment. The methods and results for consequential events in both workstreams are presented in Chapter 6.

3 DATA SELECTION AND DEFINITIONS

3.1. Description of data sources

This section describes the three data sources used in the study. The two primary sources, namely the European Central Repository (ECR) dataset and recorded flight data, are described in terms of their origin, composition, and their respective contributions to the analysis. A third source, exposure data, is used to normalise occurrence counts and compute exposure-adjusted SPIs. As several candidate datasets were considered for this purpose, the section also presents the trade-offs between the available exposure data sources and provides the justification for the selected data source.

3.1.1. ECR data

The European Central Repository (ECR) is the central European database for aviation occurrence reporting, established under Regulation (EU) No 376/2014 [4] on the reporting, analysis and follow-up of occurrences in civil aviation. The repository is managed by the European Union Aviation Safety Agency (EASA) and consolidates occurrence reports submitted by the National Aviation Authorities (NAAs) of the 31 EASA Member States, comprising the 27 Member States of the European Union together with four European Free Trade Association (EFTA) States participating in EASA: Iceland, Liechtenstein, Norway and Switzerland. The ECR constitutes one of the core data sources of the Data4Safety (D4S) programme, providing a harmonised repository of safety occurrence information to support safety analysis at the European level.

Under Regulation (EU) No 376/2014, aviation stakeholders are required to report occurrences that endanger or that, if not corrected or addressed, could endanger an aircraft, its occupants, or any other person. This mandatory reporting obligation applies to a broad range of organisations and personnel, including aircraft operators, maintenance organisations, air navigation service providers (ANSPs), aerodrome operators, design and production organisations, manufacturers, and other entities involved in civil aviation. For organisations certified by an EASA Member State, this obligation applies regardless of where the occurrence takes place, including operations conducted outside the territory of the Member States. Conversely, operators and organisations certified by non-EASA States are required to report occurrences when they take place within or over the territory of an EASA Member State. Reports are initially submitted to the competent National Aviation Authority, which validates the information and consolidates reports originating from different parties involved in the same safety event into a single occurrence record before transmission to the ECR. As a result, a single occurrence may contain complementary information provided by multiple stakeholders, offering a more comprehensive description of the event than any individual report.

Each occurrence record combines structured information, encoded using the ECCAIRS2 (E2) taxonomy, with unstructured narrative fields describing the circumstances, causes and consequences of the occurrence. The structured attributes capture operational, technical and safety-related information such as occurrence categories, event types, aircraft characteristics, flight phase, injuries and damage, while the narratives

provide contextual information that may not be represented within the taxonomy. The combination of structured and unstructured data makes the ECR particularly suitable for both rule-based analyses and advanced text mining techniques.

Despite its richness, the ECR is an occurrence reporting system rather than a complete record of all flights or operational events. The dataset therefore reflects the reporting behaviour of organisations and individuals and is inherently subject to reporting biases. In particular, turbulence encounters that result in injuries, aircraft damage, operational disruptions or other reportable safety events are significantly more likely to be reported than turbulence encounters that are successfully managed without any operational consequences. Therefore, the ECR should be interpreted as representing the population of reported turbulence occurrences, rather than the total number of turbulence encounters experienced during flight operations. The temporal coverage of the ECR dataset used in the present study is 2015 to 2025.

Additional limitations arise from the human-generated nature of occurrence reports. The completeness and consistency of structured attributes may vary between reporting organisations and Member States, while some information may only be documented within the narrative fields. Furthermore, differences in reporting practices, terminology and the level of detail provided by reporters introduces variability in the recorded information. A more detailed analysis on the ECR limitations is presented in Section 7.2.

Furthermore, under Commission Implementing Regulation (EU) No 923/2012 laying down the Standardised European Rules of the Air (SERA), SERA.12005 the pilot-in-command shall make a special air-report whenever hazardous conditions are encountered, including, among other things, severe turbulence, severe icing, severe mountain wave, thunderstorms, hail, heavy dust storm or sandstorm, volcanic ash cloud, and pre-eruption volcanic activity or a volcanic eruption. The report is to be made as soon as practicable to the appropriate air traffic services unit and serves to support the dissemination of safety-relevant information to other aircraft and authorities

3.1.2. Recorded flight data

Flight Data Monitoring (FDM) is the process of collecting and analysing data recorded onboard aircraft during flight operations through systems such as the Flight Data Recorder (FDR) or Quick Access Recorder (QAR). These systems capture a wide range of flight parameters describing aircraft performance, flight dynamics, aircraft system status, and pilot actions, providing valuable information for safety monitoring and operational analysis. In the context of this report, the term “recorded flight data” is used to refer to these recorded aircraft flight parameters and time traces. Although such data are used by airlines within their FDM programmes and are therefore sometimes referred to as “FDM data” in the broader context of the Data4Safety (D4S) programme, the present study analyses the underlying recorded flight data rather than specific FDM events generated by individual airline FDM programmes. The term “recorded flight data” (or simply “flight data” for short) is therefore used consistently throughout this report to refer to this data source.

Within the Data4Safety framework, recorded flight data provided by participating airlines is processed through a standardised and structured data processing pipeline, consisting of the following steps: data ingestion, parameter decoding, parameter homogenisation, flight identification, and data quality validation. This process ensures that data originating from different airlines and aircraft configurations is standardised and can be consistently analysed within a common framework.

The recorded flight data used in the present study is derived from the Data4Safety programme and accessed via its data-sharing platform. For the purpose of the current study, recorded flight data from six participating airlines has been used in the analysis. Prior to its use, the dataset has undergone the complete processing pipeline together with dedicated parameter cross-checking activities performed with the corresponding airlines to ensure data quality, parameter consistency, and reliability of the decoded information.

The temporal coverage of the analysed flight data extends from 2023 to 2025, representing a study period of three years. Based on this data availability, a total of 4.4 million flights have been included in the study sample, providing a large-scale dataset for the identification and characterisation of in-flight turbulence events. Although the temporal coverage of the recorded flight data sample is significantly shorter than the 11-year period of ECR data, the sample is sufficiently large and provides detailed identification and characterisation of turbulence events that will provide valuable and complementary insights for the current study.

Given the diversity of participating operators and fleet compositions, the dataset includes multiple aircraft types and variants. However, due to the current composition of the available data, 99% of flights correspond to narrow-body aircraft, which therefore represent the largest share of the analysis sample.

The aircraft types currently included in the recorded flight data, together with their distribution within the sample, are presented below.

Aircraft Types within the scope of the study: **Airbus A320, Airbus A319, Airbus A321, Airbus A330, Airbus A320-NEO, Boeing 737 NG, and Boeing 737 MAX**

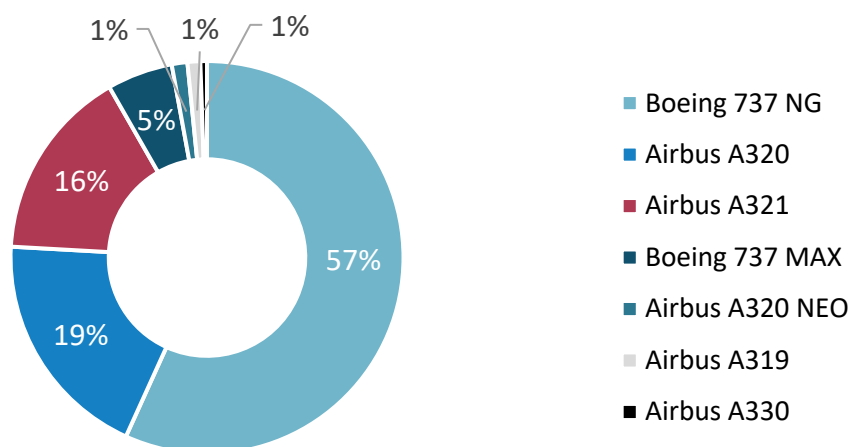


Figure 2 - Distribution of flights by aircraft type within the recorded flight data

3.1.3. Exposure data

The third data source used in the present study is the exposure dataset. The recorded flight data directly provides the total number of flights against which turbulence events can be normalised. The ECR dataset, by contrast, contains only reported occurrences, while the total number of flights corresponding to the ECR data volume are not recorded within the repository. Exposure data is therefore required to compute SPIs per-flight from the ECR workstream. The selection of an exposure dataset therefore plays a crucial role in the analysis of the ECR data.

Three candidate exposure datasets were evaluated: **Eurocontrol**, **Eurostat**, and **ADS-B**:

- **Eurocontrol**, through its Aviation Intelligence Unit, publishes monthly IFR flight statistics covering the European Civil Aviation Conference (ECAC) area, encompassing 44 Member States. The ECAC member states encompass the 31 EASA member states, plus an additional 13 states. Specific aggregated data is available for the present study through an agreement between Eurocontrol and EASA, who grants usage rights for this data within the context of the D4S programme.
- **Eurostat**, the statistical office of the European Union, similarly provides publicly available aviation movement data for EU Member States, collected under Regulation (EC) No 437/2003, with coverage extending to EU airports and routes [5].
- **Automatic Dependent Surveillance-Broadcast (ADS-B)** data, derived from aircraft position broadcasts collected through a network of ground and satellite receivers, offers broad geographical coverage and historical records are available to the D4S programme.

The objective of the selection process is to identify the exposure set that best aligns with the available ECR data volume and achieves the lowest possible normalisation error, ensuring a strong match between exposure data and underlying data. The selection of an exposure dataset from the three available options was guided by two criteria:

- The **temporal coverage** of the candidate dataset relative to the ECR analysis period of 2015-2025; and
- The **coverage alignment** between the exposure dataset’s flight coverage and the population of flights that generate ECR reports, namely EASA member state operators that fall under Regulation (EU) No 376/2014 and provide occurrence reports to the ECR.

The use of ADS-B was discarded due to its limited temporal coverage. The available dataset spans only 2024-2025, which would exclude the majority of the ECR analysis period and severely limit the data normalisation. The additional effort required to construct routes and operator breakdowns from raw ADS-B records further reinforced the decision to discard this dataset.

The choice between Eurocontrol and Eurostat datasets was made on the basis of flight coverage. The turbulence-related ECR occurrences that are included in the study were analysed by operator type (EASA Member State operator or external operator) and route type (both origin and destination within EASA Member States; one endpoint within EASA Member State and one outside EASA Member State; or both endpoints outside EASA Member States). This produces a matrix of six occurrence categories, illustrated in Figure 3.

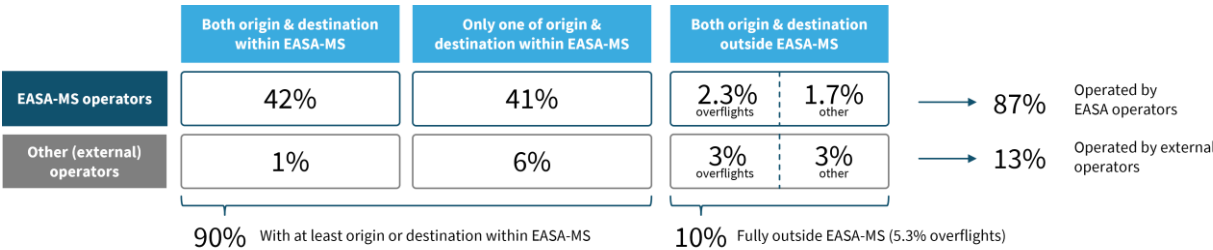


Figure 3 - Breakdown of ECR occurrences by operator and route type

Both Eurocontrol and Eurostat provide adequate coverage for the first two route types – routes fully within EASA Member States and routes with one endpoint outside – for both operator categories. The main difference lies in the third route type: flights with both origin and destination outside EASA Member States. These flights are primarily as overflights – flights that transit EASA Member State(s) airspace without departing from or arriving at an EASA Member State. Eurocontrol includes overflight data within its statistics, whereas Eurostat does not. Given that overflights represent a non-negligible share of ECR occurrences, as shown in Figure 4, Eurocontrol data was selected as the exposure dataset.

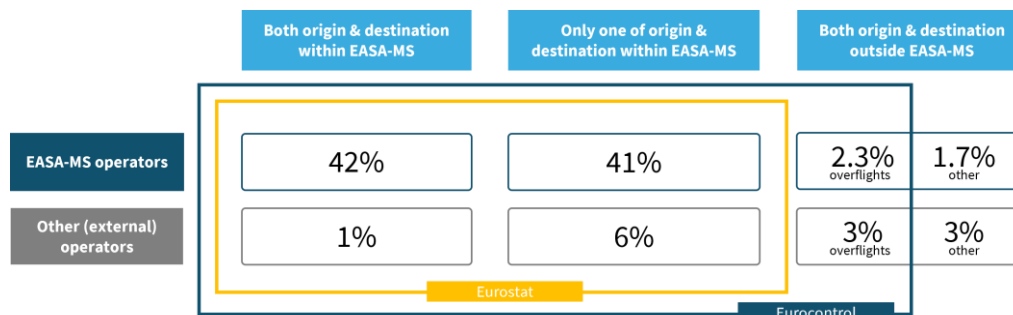


Figure 4 - Coverage alignment between exposure datasets and ECR occurrences

The Eurocontrol dataset provides monthly aggregated flight volumes across the relevant European States, against which occurrence counts can be normalised to produce exposure-adjusted metrics. Eurocontrol flight statistics are published at a monthly granularity, with coverage that includes all EASA Member States, providing breakdowns by operator state and route category which is consistent with the structure used in the ECR occurrence analysis.

The limitations associated with the use of exposure data and their potential implications for the analysis are discussed in Section 7.2.

3.2. Definition of scope

The scope of this directed study has been defined to support the objectives described in section 1.3, namely the assessment of emerging aviation hazards through data-driven safety analysis, and the directed study definition presented in section 1.4. In particular, the study aims to establish a baseline characterisation of in-flight turbulence encounters affecting commercial air transport operations, providing quantitative evidence that can support future assessments of the impact of climate change on aviation safety.

To achieve this objective, common scope criteria have been established across the three data sources considered in this study: ECR occurrence reports, recorded flight data, and exposure data. Although each dataset has different characteristics and operational constraints, the adopted scope ensures that the analyses remain comparable. The same scope applies to all three data sources, even though their practical application varies with each dataset's characteristics, providing a common analytical basis for the resulting Safety Performance Indicators (SPIs).

3.2.1. Operational scope

The study is limited to Commercial Air Transport (CAT) operations involving Complex Aircraft, following the classification adopted by EASA. This includes commercial passenger and cargo operations performed by complex aeroplanes with a maximum certificated take-off mass exceeding 5,700 kg, equipped with one or more turbofan engines or more than one turboprop engine. This operational scope has been selected as it aligns the occurrence reports analysis with the flight data available through the Data4Safety programme,

which is inherently limited to this category of operation. Consequently, although this filter is only explicitly applied to the ECR data, it establishes a common operational scope across all datasets analysed in this study.

3.2.2. Temporal scope

The temporal scope covers the period from 1 January 2015 to 31 December 2025, corresponding to an 11-year observation period. The lower boundary was selected to coincide with the implementation of Regulation (EU) No 376/2014, which introduced the current European occurrence reporting framework and significantly improved the harmonisation and consistency of safety occurrence reporting across EASA Member States. The temporal coverage differs between the analysed datasets. The ECR provides occurrence reports throughout the complete study period (2015-2025), whereas the recorded flight data currently available through the Data4Safety programme only covers the period 2023-2025. Analyses involving recorded flight data are therefore restricted to this shorter timeframe. Additionally, the exposure dataset has coverage starting in 2019. Consequently, when ECR data is normalised with exposure data the results are limited to the period starting in 2019. In summary:

- The ECR data covers the complete study period, namely 2015-2025
- When ECR data is normalised using exposure data, the temporal coverage is reduced to 2019-2025
- The recorded flight data has a temporal scope of 2023-2025

3.2.3. Geographical scope

The geographical scope of the study is worldwide and therefore no geographical filtering was applied to the ECR dataset in general. Nevertheless, it should be noted that the geographical coverage of the available ECR data is inherently limited by the scope of ECR reporting obligations and the stakeholders that report to the ECR. In addition, as introduced in Section 3.1.3, when normalizing ECR data against the exposure dataset to compute metrics on a per-flight basis, the ECR data is filtered to ensure an adequate match with the geographical coverage of the exposure data. The ECR data, when exposure is being computed, is filtered ensuring that at least one of the following three conditions is met:

- The origin airport is located in an EASA Member State; or
- The destination airport is located in an EASA Member State; or
- The state/area of the occurrence is an EASA Member State

The geographical scope of the recorded flight data is limited by the operators that provide data to the D4S programme. As described in Section 3.1.2, the recorded flight data contains data from 6 different European operators. Its geographical scope is therefore limited by the operational regime of those operators. As a result, the recorded flights are mostly concentrated in and around Europe, comprising both flights entirely within Europe and flights going to worldwide destinations based on the operational coverage of the included operators.

3.2.4. Turbulence scope

The study focuses on in-flight atmospheric turbulence relevant to the assessment of future climate-related aviation hazards, as introduced in section 1.4. Accordingly, the study includes the following categories of atmospheric turbulence:

- Clear-air turbulence (CAT); and
- Convective turbulence

These categories represent atmospheric turbulence phenomena whose frequency or severity may be influenced by changing meteorological conditions and are therefore directly relevant to the objectives of the ALBATROS project.

Conversely, wake turbulence (including wake vortex), terrain-induced turbulence, and mountain wave turbulence are outside the scope of this directed study. Occurrences associated with these phenomena are identified and excluded during the occurrence identification process of the ECR data.

3.2.5. Flight phase scope

The study considers turbulence encounters occurring during the Initial Climb, Climb, Cruise, Descent, and Approach phases of flight. These phases represent the airborne operational context addressed by this directed study. Turbulence encounters occurring during Take-off, Final Approach, Landing, Taxi, Standing, and other airport-related operations are outside the scope of this study.

3.2.6. D4S Data Governance conditions and scope of results

Since the present study has been conducted within the framework of the D4S programme, the dissemination of its results is subject to the programme's overall governance framework, including Data Governance (DaGo), Programme Charter, and Rules and Procedures. The DaGo framework defines the procedures governing how data are accessed, processed and disseminated within the D4S platform, with the objective of protecting the interests of the participating data owners while enabling collaborative, data-driven aviation safety analyses. The framework is founded on the D4S programme's core principles of collaboration, voluntariness, confidentiality, just culture and safety improvement.

To prevent the direct or indirect identification of participating aircraft operators, DaGo establishes minimum representativeness requirements that any operational context must satisfy before aggregated results can be disclosed (no single operator exceeding 80% of the flights in a context; no two operators exceeding 90%). The present study therefore adheres to the conditions and constraints as established by the current version of the D4S Data Governance policies at the time the study was conducted (version 2.2).

As a consequence of the application of these policies, not all analyses that are technically feasible can be reported. In such cases, the corresponding results cannot be disclosed, even if the underlying data are available and statistically meaningful. Throughout this report, some figures, tables, or levels of detail have

therefore been omitted, aggregated to a higher level of abstraction, or have been simplified to ensure compliance with the DaGo framework. These restrictions should be interpreted as data governance constraints rather than analytical limitations, and they do not affect the underlying methodology or the validity of the analyses performed.

3.3. Definition of Safety Performance Indicators

Safety Performance Indicators (SPI) form the backbone of the characterisation and analyses conducted across both the ECR and flight data workstreams. Each SPI provides a quantified, consistently defined measure of a specific aspect of turbulence that is relevant for safety analyses. Collectively, they serve four functions:

- Characterising the circumstances under which turbulence events occur;
- Quantifying the event frequency of turbulence and consequential events;
- Expressing SPIs on an exposure-adjusted basis (normalised per flight);
- Providing the results from which conclusions and recommendations can be drawn.

Figure 5 illustrates the role of SPIs within the overall analytical process.

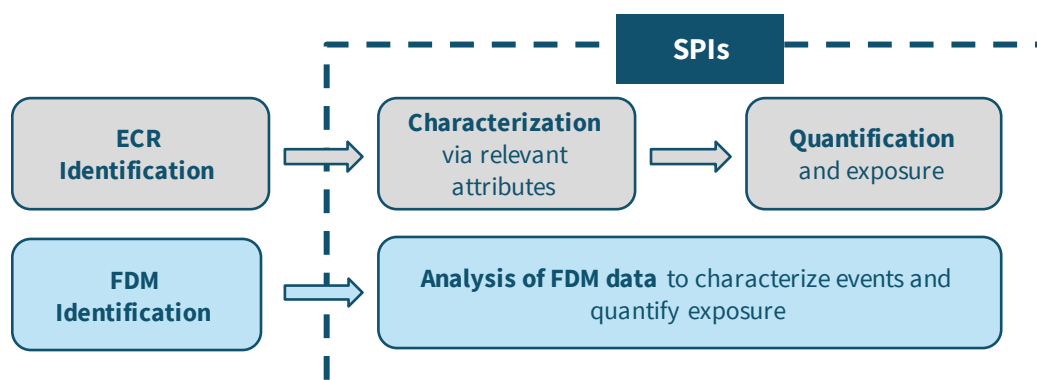


Figure 5 - Role of SPIs in the characterisation and analysis exercise

Where possible, SPIs are designed to support comparative analyses between the two datasets, while acknowledging that direct equivalence between the two cannot be assumed due to inherent differences in data availability, collection methods, and processing procedures.

SPIs have been developed through a structured three-stage process, illustrated in Figure 6.



Figure 6 - Process for SPI generation

The first stage identifies a set of analysis themes – the broad analytical dimensions considered relevant to turbulence safety. Examples of relevant themes include, among others, turbulence intensity, flight phase, altitude, aircraft type, and injury outcome. The second stage derives specific research questions within each theme. These questions define precisely what the analysis and SPIs seek to answer. For example: *“What is the distribution of turbulence occurrences by turbulence intensity?”* Or *“What is the geographical distribution of turbulence events?”*. Each question is framed in such a way that it could be answered using the available data and provides meaningful results in the context of the safety assessment of in-flight turbulence. The third stage translates each research question into one or more SPIs. Every SPI is defined by three components:

1. **The measure** (what is being counted or quantified);
2. **The grouping or segmentation** (the dimension across which results are broken down); and
3. **The normalisation** (the denominator used to adjust for differences in exposure or dataset composition).

For example, a research question concerning the frequency of turbulence events by turbulence intensity yields the SPI: “The number of turbulence occurrences by turbulence intensity per 1,000 flights”, where the measure is the count of turbulence occurrences, the grouping is the turbulence intensity categories, and the normalisation is the flight volume (i.e. exposure data). Several quantification approaches are used, each serving a distinct analytical purpose:

- **In absolute terms** – Provides the count of turbulence occurrences (ECR) or turbulence episodes (recorded flight data) in absolute numbers, without normalisation.
- **As a percentage of turbulence occurrences** – Expresses how a given set of turbulence events is distributed across a particular dimension, without reference to the overall traffic volume (exposure). This is appropriate when the objective is to understand the characteristics of the volume of turbulence occurrences by itself. For example, the percentage of turbulence occurrences resulting in injury indicates how frequently an injury is reported given that a turbulence occurrence has taken place. The same approach can be applied to other consequences, such as serious injuries, aircraft damage or operational disruptions. These percentages characterise the reported turbulence occurrences but do not account for differences in flight volume. This normalisation is only applied in the ECR workstream and is used to assess the relative contribution of turbulence occurrences to the overall reported safety occurrences.
- **Normalised with exposure data** – Occurrences normalised per 1,000 flights express the frequency of a given subset of turbulence events relative to the flight activity. This approach provides an exposure-adjusted safety performance measure, enabling meaningful comparison across time periods or operational categories that differ in traffic volume. Unlike the percentage-based normalisation described above, this approach supports analysis of turbulence events independent of flights volume. For instance, the number of turbulence occurrences leading to a severe injury per 1,000 flights quantifies the rate at which this particular outcome occurs, providing a measure of this outcome independent of the traffic volume. As discussed in Sections 3.1 and 3.2, metrics

that rely on normalisation with exposure data are limited in temporal scope to 2019 onwards and in geographical scope to flights with an origin, destination, or State/Area of Occurrence within an EASA Member State.

The list of SPIs developed for the characterisation and analysis of the two data sources (ECR data and recorded flight data) can be found in Appendix A . The SPIs are broken down by themes, with each theme containing one or more research questions that guide and structure the SPI definition. Detailed pseudocodes for the computation of each SPI can also be found in Appendix A, in addition to several important notes regarding their definition and implementation.

4 DATA PROCESSING AND TURBULENCE IDENTIFICATION

This chapter describes the processing of the two key datasets of the study introduced in Chapter 3 and the methodologies used to identify turbulence-related events within each data source. The processing steps are tailored to the characteristics of each dataset to ensure that the resulting data are suitable for the analyses presented in this study. For the ECR data, the methodology focuses on identifying which recorded occurrences are related to turbulence (Section 4.1), while for the recorded flight data the focus is on detecting individual turbulence episodes within the dataset (Section 4.2).

4.1. Identification of turbulence-related ECR occurrences

The objective of the event identification process was to compile a comprehensive dataset of in-flight turbulence encounters from the ECR database for subsequent characterisation and analysis. Given the nature of occurrence reporting systems, no single database attribute can reliably identify all turbulence-related occurrences. Although many occurrence reports are explicitly classified using the appropriate ECCAIRS2 (E2) taxonomy, others contain only partial structured information or describe the turbulence encounter exclusively within the free-text narrative of the occurrence report.

To maximise both the level of completeness and precision, a multi-stage identification pipeline was developed. The pipeline combines deterministic query logic based on structured ECCAIRS2 taxonomy attributes, complemented with text mining techniques and Large Language Model (LLM) validation. Each stage complements the previous one by progressively identifying additional relevant occurrences while filtering out occurrence reports that do not relate to a turbulence encounter.

The overall process consists of the following steps:

1. Definition of the data selection criteria and initial filtering of the ECR dataset based on the scope defined in Section 3.2.
2. Identification of candidate turbulence occurrences using structured ECCAIRS2 taxonomy attributes and values.
3. Identification of additional candidate occurrences through keyword searches over occurrence narrative and free-text attributes.
4. Validation of all candidate occurrences using an LLM to confirm their relevance to the study.
5. Generation of the final dataset used for the subsequent characterisation and Safety Performance Indicator (SPI) analysis.
6. Application of data quality enhancement techniques to improve the completeness and consistency of the occurrence records before the characterisation and Safety Performance Indicator (SPI) analysis.

The above steps are presented in detail in the text below, while the limitations associated with this methodology are presented in Section 7.2.

4.1.1. Data selection and initial filtering

The scope defined in Section 3.2 was converted into a set of filtering criteria applied to the ECR occurrence database in order to obtain the initial dataset for the turbulence event identification process. The filtering was implemented using the ECCAIRS2 taxonomy attributes and values, corresponding to temporal, operational and aircraft characteristics defined in the scope of the present study (see Section 3.2). The specific filtering criteria used can be found in Appendix B.

The operational scope was implemented by selecting only Commercial Air Transport (CAT) operations involving Complex Aircraft. Since no single ECCAIRS2 taxonomy attribute uniquely identifies this aircraft category, the filtering logic combined multiple aircraft-related attributes, including the Operation Type, Aircraft Category, Mass Group, Number of Engines, and Propulsion Type, to identify aircraft category matching the study scope.

The flight phase scope was implemented using the Occurrence Detection Phase attribute. Occurrences reported during the Initial Climb, Climb, En-route, Descent, and Approach phases were retained in the data sample. In addition, occurrences with an unreported or unknown detection phase were also included at this stage, as the flight phase were subsequently validated and, where possible, recovered through the LLM-based analysis of the occurrence narratives. This approach avoids prematurely excluding relevant turbulence encounters due to incomplete taxonomy classifications of occurrence reports.

Based on these criteria, an initial filtering step was applied to the complete ECR dataset to retain only occurrence records matching the defined temporal, operational, and geographical scope. This process resulted in an initial working dataset of approximately 749,000 occurrence records from which turbulence encounters were subsequently identified through the event identification pipeline described in the following sections.

4.1.2. Identification of turbulence events using structured occurrence data

Following the initial filtering of ECR records, the candidate turbulence occurrences were identified using the structured information available within the ECR records in the taxonomy attributes and values. Due to the flexibility of the ECCAIRS2 taxonomy model, turbulence encounters may be classified in different parts of the template of the occurrence report, depending on the reporting practices of the originating organisation. Consequently, relying on a single taxonomy attribute would lead to an incomplete identification of relevant events.

To maximise the detection of turbulence encounters in the initial data sample, the identification logic combined information from multiple ECCAIRS2 taxonomy attributes [3]. By combining multiple ECCAIRS2 taxonomy attributes rather than relying on a single one, the query captures occurrences that may have been coded differently by reporting organisations, thereby reducing the likelihood of missing relevant

events due to variations in reporting practices. An occurrence was considered a candidate for the study if it was directly related to a turbulence encounter consistent with the scope defined in Section 3.2. The exact query used to detect such occurrences can be found in Appendix B.

This deterministic identification stage constitutes the primary mechanism for selecting turbulence occurrences from the ECR database. Nevertheless, because the structured taxonomy is not always fully populated, some genuine turbulence encounters may remain undetected even though they are clearly described in the occurrence narratives. Consequently, a complementary narrative-based identification process was applied, as described in the following section.

4.1.3. Narrative-based identification of turbulence events

While the rule-based query identifies the majority of turbulence occurrences through the ECCAIRS2 taxonomy attributes, it cannot capture events for which turbulence has not been explicitly classified in one of the relevant taxonomy attributes. However, occurrence reports frequently contain detailed free-text narratives describing the circumstances of the event, often including references to turbulence - even if the reports have not been classified in taxonomy attributes as a turbulence event. To improve the completeness of the identified dataset, a complementary narrative-based identification stage was applied to all occurrence records within the study scope. The objective of this stage was to identify additional candidate turbulence occurrences by analysing the narrative fields and detecting certain key words associated with turbulence encounters. This stage should reduce the likelihood of excluding relevant events due to incomplete or inconsistent use of the ECCAIRS2 taxonomy. The approach intentionally prioritises recall over precision², as candidate occurrences are subsequently validated using a Large Language Model (LLM).

The search was performed in the narrative fields available within the ECR occurrence records, namely Occurrence “Headline”; “Narrative text” in Narrative, Aircraft Narrative, Aerodrome Narrative and ANS Narrative; and Reporting history “Reporter’s Description”, “Conclusions”, and “Analysis/follow up”. The narrative search strategy combined aviation domain expertise with statistical text analysis techniques. Initially, aviation experts identified terminology commonly used to describe turbulence encounters. In addition to direct references to turbulence (e.g., *turbulence*, *clear-air turbulence* or *wind shear*), the keyword catalogue also included terms describing meteorological conditions, aircraft responses and operational consequences that are frequently associated with turbulence encounters, such as *gust*, *downdraft*, *stick shaker*, *overspeed* or *VMO*. Although some of these terms are not exclusively related to reports of turbulence encounters, their inclusion increases the likelihood of identifying relevant

² Recall and precision are standard metrics for evaluating classification or search performance. Recall measures the proportion of actual turbulence occurrences successfully identified (minimising missed events), while precision measures the proportion of identified occurrences that are genuine turbulence events (minimising false positives). Prioritising recall means the method favours capturing as many true events as possible, even at the cost of flagging some irrelevant ones, since the subsequent LLM validation step is used to validate the selected occurrences.

occurrences in which turbulence is reported indirectly rather than explicitly. The full list of keywords used is:

Turbulence	Gust	CB
Turbulent	Surge	Cumulonimbus
Turbulences	Bust	Overspeed
Bumpiness	Wave	Strong wind
Downdraft	Gusty	Strong winds
Updraft	Gusty wind	Bumpy
Air roughness	Gusty winds	Stick shaker
Rough air	Gusting	Convective
Air pocket	Windshear	Jet stream
Air pockets	Wind shear	CAT
Oscillation	Wind shears	Jolt
Oscillations	Wind-shear	Downburst
Unstabilised approach	TS	MMO
Speed variation	Thunderstorm	VMO

The initial keyword catalogue was subsequently expanded and refined using a Term Frequency-Inverse Document Frequency (TF-IDF) analysis of the narratives from a set of confirmed turbulence occurrences, enabling the identification of additional relevant keywords or search terms. Furthermore, lexical variants of the selected keywords were automatically generated using lemmatization dictionaries³, and equivalent terms were incorporated for the most frequently used languages⁴ represented within the ECR occurrence database. This ensured that differences in wording, grammatical forms and reporting language did not adversely affect the identification process.

The resulting keyword catalogue was applied to the selected narrative fields to retrieve additional candidate occurrences that had not been identified through the rule-based query. As the presence of a keyword alone does not necessarily confirm that an occurrence is relevant to the study, all records identified through either the structured query or the narrative search were subsequently subjected to a validation process using a Large Language Model (LLM), as described in the following section.

³ Lemmatization dictionaries map inflected word forms (e.g., plurals, verb conjugations, comparatives) to their base or dictionary form (the "lemma"). For example, "turbulent," "turbulence," and "turbulences" would all resolve to a common lemma, allowing keyword searches to capture grammatical variants of a term without needing to list each one manually.

⁴ The languages included in the keyword search are: English, Romanian, Italian, Portuguese, Galician, Spanish, Catalan, French, German, Afrikaans, Dutch, Danish, Swedish, Finnish, Icelandic, Croatian, Hungarian, Estonian, Norwegian, Faroese, Lithuanian, Latvian, Slovenian, Polish, Czech, and Slovak.

4.1.4. LLM-based occurrence validation

The final stage of the event identification pipeline consisted of validating all candidate occurrences identified through the rule-based query and the narrative-based keyword search. The main objective of this stage was to confirm whether each candidate occurrence report represented a genuine in-flight turbulence encounter meeting the scope of this study. A second objective was to classify the type of turbulence and flight phase reported in the occurrence report.

The validation was performed using the Claude Haiku 4.5 Large Language Model (LLM). The model was selected due to its ability to accurately interpret both structured occurrence attributes and unstructured narrative text while consistently following detailed, rule-based instructions. In particular, the model is capable of analysing information distributed across multiple narrative fields, extracting only information explicitly stated in the occurrence report, and producing structured outputs suitable for subsequent integration into the data processing pipeline. For each candidate occurrence, the model was instructed to rely exclusively on the information contained within the occurrence record free-text attributes and not to infer facts that were not explicitly reported. The validation process required the model to determine whether the occurrence corresponded to a turbulence encounter relevant to the scope of this study. Where turbulence was confirmed, the model was further required to classify both the reported turbulence type and the phase of flight in which the event occurred.

The turbulence classification was performed according to the following predefined categories, along with the ECCAIRS2 definition of each category:

- Clear-air Turbulence (CAT)
- Convective Turbulence
- Terrain-Induced Turbulence
- Mountain Wave Turbulence
- Vortex/Wake Turbulence
- Wind Shear Turbulence
- Not Reported

In addition, the model identified the flight phase associated with the turbulence encounter using the following values, defined in the ECCAIRS2 taxonomy, including a segregation of en-route phase between climb, cruise and descent:

- Take-off
- Initial Climb
- Climb
- Cruise
- Descent
- Approach
- Final Approach

- Landing
- Not reported

The flight phase classification was incorporated into the validation process to ensure consistency with the operational scope of the study and to support the subsequent filtering and characterisation of occurrences according to the relevant phases of flight. The model produced a fully structured JSON response for each analysed occurrence, facilitating the automated integration of the validation results into the event identification pipeline and enabling subsequent quality assurance and analysis.

To assess the reliability of the LLM-based validation, a representative sample of 200 occurrence records was manually reviewed by aviation experts and compared against the model predictions. The validation results are summarised in Table 2.

Table 2 - Manual validation of the LLM-based occurrence classification

Classification outcome	Number of occurrences
Correct Turbulence	86
Incorrect Turbulence	0
Correct Non-turbulence	112
Incorrect Non-turbulence	2

The results demonstrate a high level of agreement between the LLM predictions and the expert assessment. Of the 200 manually reviewed occurrences, 198 were correctly classified, corresponding to an overall classification accuracy of 99.0%. No false-positive turbulence occurrences were identified by the model, while only two turbulence occurrences were incorrectly classified as non-turbulence events. These results provide confidence that the LLM constitutes a reliable validation mechanism within the event identification pipeline. This effectively reduces the number of false positives introduced during the narrative-based candidate retrieval stage while preserving a high level of recall for relevant turbulence occurrences.

The structured output generated by the LLM was subsequently filtered according to the scope of the directed study. Only occurrences classified as confirmed turbulence encounters, associated with turbulence types within the scope of the analysis, and occurring during the flight phases considered by the study (Initial Climb, Climb, Cruise, Descent, and Approach) were retained.

4.1.5. Final event dataset

The complete event identification pipeline progressively refines the occurrence dataset by combining deterministic queries, narrative analysis and LLM-based validation. Starting from the initial ECR dataset within the temporal, operational and geographical scope of the study, each processing stage contributes either to identifying additional candidate turbulence occurrences or to filtering out those that do not genuinely correspond to a relevant turbulence event. This ensured that the retained occurrences are representative of the phenomenon under study.

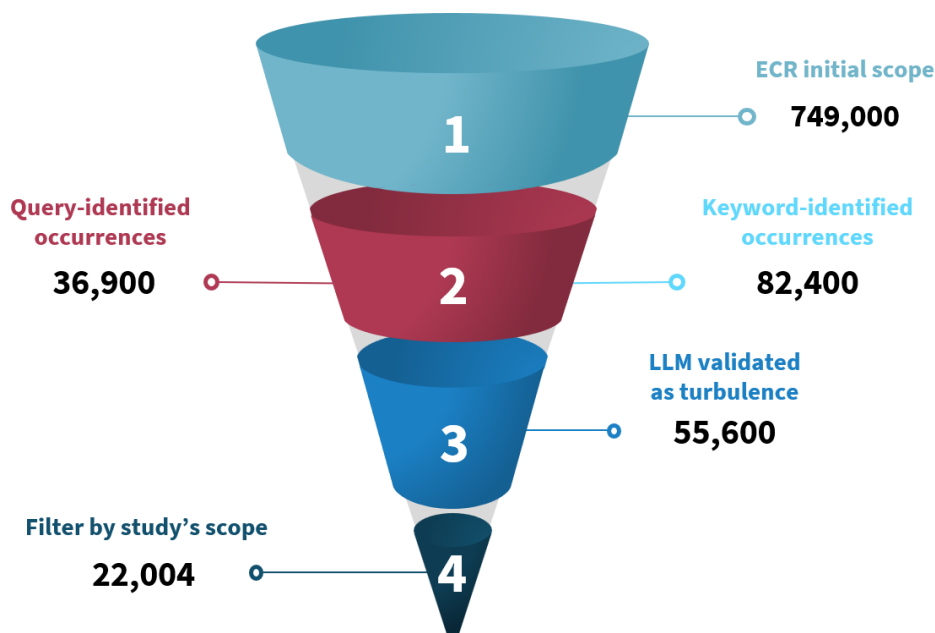


Figure 7 - Evolution of the volume of occurrences throughout the turbulence identification pipeline

As illustrated in Figure 7, the initial filtering produced a working dataset of approximately 749,000 occurrence records. The rule-based identification stage detected 36,900 occurrences explicitly classified as turbulence using the structured ECCAIRS2 taxonomy. The narrative-based keyword search then identified an additional 82,400 candidate occurrences, which were considered potential turbulence encounters and forwarded to the LLM validation stage together with the rule-based results. The LLM subsequently assessed all candidate occurrences to confirm whether they corresponded to genuine turbulence encounters, resulting in a consolidated dataset of approximately 55,600 validated turbulence occurrences. Finally, the structured outputs generated by the LLM were filtered according to the scope of the directed study, retaining only occurrences associated with the turbulence types and flight phases considered within the project. This final filtering step produced a final dataset of 22,004 validated turbulence occurrences, which constitutes the basis for the characterisation and analysis of turbulence events presented in the following chapters.

4.1.6. Data quality improvements

The occurrence reports are submitted to the ECR by diverse aviation stakeholders. Accordingly, the application of the taxonomy attributes and values, and the level of completeness of certain attributes may depend on reporting practices and may vary across different types of occurrences. Some fields therefore exhibit missing or incomplete information, particularly for attributes that are not mandatory, or are inconsistently reported. Such data completeness issues represent an important limitation when analysing occurrence data and may negatively affect the characterisation and analysis of safety events if not properly addressed. To compute the SPIs defined in Section 3.3, contextual and consequential information of the

occurrence must be collected. Beyond the completeness and taxonomy application issues described above, a further limitation relates to the level of information that is available in the report itself. Even if the taxonomy is applied consistently and completely, certain contextual or consequential details relevant to the characterisation of turbulence occurrences may simply not have been reported by the reporter or reporting entity. This presents another limitation, as it concerns the availability of relevant information rather than the consistency or completeness of taxonomy usage.

To mitigate the impact of these limitations, a series of data quality enhancement measures were applied before performing the event characterisation and calculating the SPIs. The objective of these measures was to improve the completeness and consistency of the attributes that are relevant to the study, thereby increasing the reliability and representativeness of the analysis. The adopted methodology combined expert-defined business rules with AI-based information extraction techniques. The business rules focused on consolidating information available across related ECCAIRS2 attributes, exploiting redundancies within the reporting structure to recover missing values and harmonise the dataset. These consolidation rules were derived from two complementary sources: the Occurrence capture semi-automation project, developed by EASA to improve the consistency and completeness of occurrence records, and secondly, the ECR Sanitization Task Team, established within the Data4Safety (D4S) programme to define standardised data quality improvements in the ECR.

Table 3 - Summary of the source of the business rules applied to each attribute

Attribute	Business rule source
UTC Date	ECR Sanitization Task Team
UTC Time	ECR Sanitization Task Team
Total Fatalities	ECR Sanitization Task Team
Total Serious Injuries	ECR Sanitization Task Team
Total Minor Injuries	ECR Sanitization Task Team
Total No Injuries	ECR Sanitization Task Team
Total Injuries Unknown	ECR Sanitization Task Team
Injury Level	ECR Sanitization Task Team
State Area of Occurrence	ECR Sanitization Task Team
Highest Damage	Occurrence Capture semi-automation project
Detection Phase	Occurrence Capture semi-automation project
Turbulence Intensity	Custom logic for the ALBATROS study

While most of the business-rule-based consolidations consist of deterministic mappings between related ECCAIRS2 taxonomy attributes, some of the implemented rules require assumptions to address missing or incomplete information in the occurrence report. These assumptions are intended to maximise data completeness while preserving internal consistency; however, they should be considered when interpreting the results presented in this report:

- **Injury and fatality-related fields.** The consolidation logic reconciled information reported across multiple ECCAIRS2 taxonomy attributes to maximise completeness while maintaining consistency. Whenever at least one of the attributes required by the consolidation logic contained a valid value

in the report, any remaining null values were interpreted as a zero. Conversely, when all injury-related attributes in a report were null, it was assumed that the occurrence did not result in injuries and the **Total Fatalities** field was set to zero as the default value.

- **Injury level.** This attribute was derived from the consolidated numerical injury counts following a severity-based hierarchy, such that it reflects the highest level of injury sustained by any individual involved in the occurrence. However, when one or more injuries were reported with **Unknown** severity (i.e., *Total Injuries Unknown* > 0) and no fatalities were recorded, the resulting **Injury Level** was assigned the value **Unknown**, as the available information did not allow the highest injury severity to be determined with confidence.

To further enhance the completeness of the occurrence reports, a Large Language Model (LLM) was employed to analyse the narrative fields associated with all turbulence events. While many relevant details are described in the free-text narratives, they are not always reflected in the corresponding structured ECCAIRS2 taxonomy attributes. The objective of the LLM-based enrichment was therefore to extract contextual and event-specific information from the narratives and convert it into structured variables that could be used during the characterisation phase. The narrative fields used as an input for this LLM were Occurrence “Headline”, “Narrative text” in Narrative, Aircraft Narrative, Aerodrome Narrative and ANS Narrative, Reporting history “Reporter’s Description”, Reporting history “Conclusions”, and Reporting history “Analysis/follow up”.

The selected model, Claude Haiku 4.5, was used through a prompt-based approach to analyse the occurrence narratives. The model was explicitly instructed to rely exclusively on information contained within the occurrence report, without inferring or introducing external knowledge. Information was extracted by classifying the narrative content according to predefined taxonomies, ensuring that the generated values were consistent and suitable for quantitative analysis. For attributes already defined in the ECCAIRS2 (E2) taxonomy, the model assigned the corresponding standardised E2 values. These included **Highest Damage, Turbulence Intensity, Turbulence Type, Flight Level, and Event Type L4**. For the later one, given the large number of possible values, a specific subset of operational and safety events related to turbulence was defined for this study. Furthermore, as multiple operational events may be described within a single occurrence narrative, the model was designed to identify and return all relevant events in their chronological order. Flight levels mentioned in the narratives were also converted into structured numerical values.

In addition to existing ECCAIRS2 taxonomy attributes, the enrichment process extracted information that is not explicitly represented within the ECCAIRS2 taxonomy but was considered relevant for the characterisation of turbulence occurrences in this study. For these variables, dedicated taxonomies were developed to ensure consistent and structured outputs across all occurrence reports. These additional attributes included the number of crew and passenger injuries, broken down by severity (fatal, serious and minor); the **Location of Injury within the Aircraft** (e.g., cockpit, passenger seating area, aisle, galley or

lavatory); and the **Activity During Injury** (e.g., seated with seatbelt fastened, standing, walking in the cabin, performing cabin service or using the lavatory).

The model was required to produce a fully structured output for every occurrence report, facilitating subsequent validation, integration into the analysis dataset, and computation of the defined Safety Performance Indicators (SPIs). This enrichment process significantly increased the availability of structured information while maintaining traceability to the information explicitly reported in the original occurrence reports.

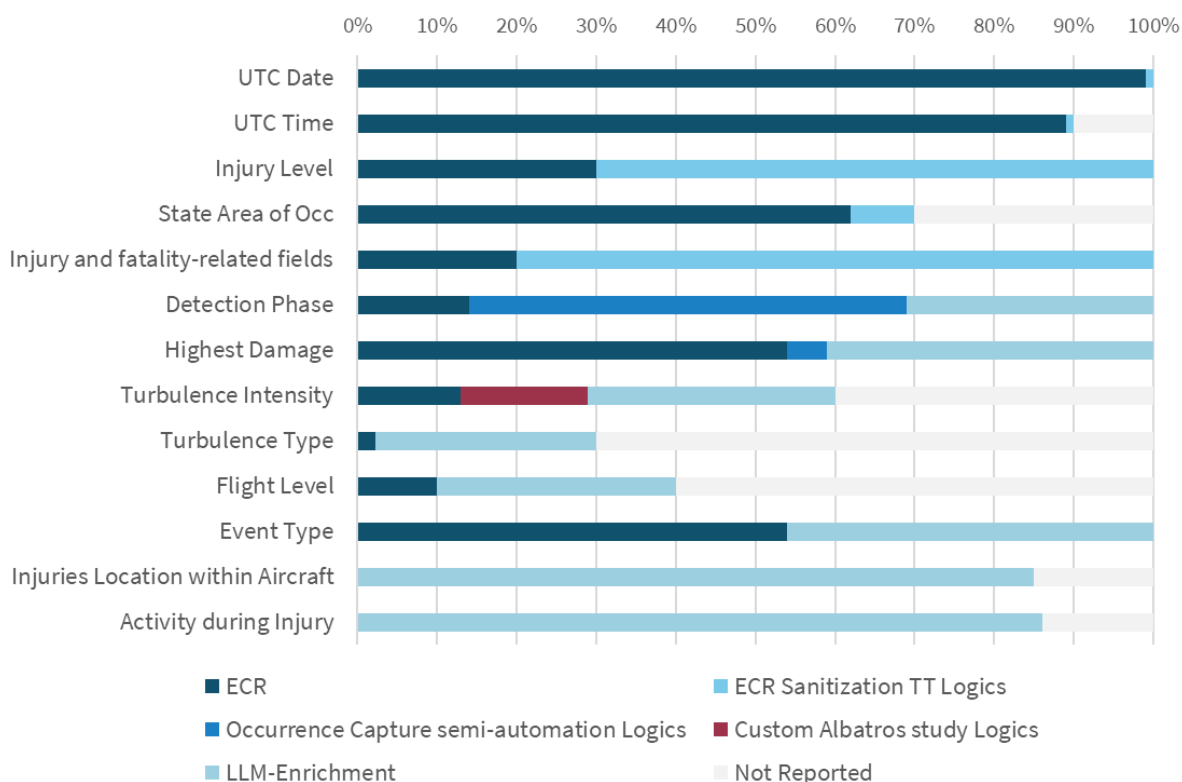


Figure 8 - Completeness of the ECR attributes that underwent data quality enhancement

Figure 8 summarises the improvements achieved through the data quality enhancement process. For each attribute, the figure shows the proportion of values originally available in the ECR data sample, the additional information recovered through the business-rule-based consolidation, the contribution of the LLM-based enrichment, and the remaining proportion of records for which no information could be obtained. The results demonstrate that the two complementary approaches address different types of data quality issues. The business-rule-based consolidation is particularly effective for attributes that already exist in the ECCAIRS2 taxonomy but were only partly populated, such as **Detection Phase**, **Injury Level**, **Total Fatalities**, **Highest Damage**, and **State Area of Occurrence**. Information on these attributes can be recovered from related taxonomy attributes through deterministic logic. In contrast, the LLM-based enrichment primarily contributes to attributes whose information is typically described only in the occurrence narratives, including **Turbulence Type**, **Flight Level**, **Event Type**, **Injury Location within the**

Aircraft, and **Activity during Injury** as well as providing additional improvements for **Highest Damage** and **Turbulence Intensity**.

Overall, the combination of deterministic business rules and LLM-based information extraction substantially increased the availability of structured information across the occurrence dataset. While some attributes continue to present incomplete coverage due to the absence of information in both the structured taxonomy attributes and the occurrence narratives, the implemented data quality measures significantly reduced the proportion of missing values. This effort provided a more complete and consistent dataset for the computation of the defined Safety Performance Indicators (SPIs) and the subsequent characterisation of turbulence events.

4.2. Identification of turbulence episodes in the recorded flight data

The identification and characterisation of turbulence events from recorded flight data requires the implementation of a multi-step processing pipeline designed to ensure data quality, reliability of sensor measurements, and robust detection of turbulence events. Figure 9 shows the required processing steps. The process begins with an initial data cleaning stage, where the flight dataset is prepared by removing non-representative records such as test flights, excluding incomplete flight records, and retaining only flights containing the set of parameters required for the analysis. A dedicated accelerometer bias correction methodology is then applied to account for potential systematic offsets in acceleration measurements, improving the reliability of the recorded acceleration sensor data prior to the turbulence event detection.



Figure 9 – Overview of the Data Preprocessing and Identification of in-flight turbulence events using recorded flight data

Once the data quality has been ensured, turbulence event identification is performed through the analysis of the Root Mean Square (RMS) of the aircraft's Z axis acceleration signal, hereafter referred to as vertical acceleration for simplicity. The signal serves as the main indicator for detecting a turbulence-induced aircraft response. Signal processing techniques are applied to separate turbulence-related accelerations from low-frequency aircraft manoeuvres, e.g. turns or initiation of a climb, allowing the identification of genuine turbulence events. Finally, the detected RMS peaks are transformed into intensity of aircraft's response using predefined thresholds. Additional contextual parameters are then incorporated to further characterise the detected events and provide a more comprehensive representation of the operational conditions under which turbulence events occur.

4.2.1. Key definitions

Some terms related to the identification of turbulence episodes in the recorded flight data play a key role in the discussion of the main findings presented in Chapter 5. For that reason, and to provide the reader

with clear definitions used in the description of the turbulence identification methodology, the definition of these key terms is provided below. Note that these definitions should be understood in the context in which they appear in the following sections.

- **Event and episode** – The term *event* refers to a single instance in which turbulence is detected. An *episode* is a group of events that occur in close temporal proximity to one another. Events within an episode could be separated by quiescent periods (i.e. periods without turbulence). The maximum temporal separation between events within an episode is 5 minutes. See Section 4.2.4 for the identification of turbulent events, and Section 4.2.6 for information regarding their aggregation into episodes
- **Intensity** – The *intensity* (or intensity level) of a turbulence event or episode in the recorded flight data refers to the intensity of the aircraft response to the atmospheric turbulence. The available parameters do not allow for the calculation of the turbulence intensity itself. Instead, intensity is based on the acceleration along the aircraft's body Z-axis (*Nz* signal), which plays a central role to the entire identification methodology. Consequently, what is being assessed is the intensity of the aircraft response to incoming turbulence, the magnitude of which depends on parameters such as wing loading, airspeed, altitude (air density), lift curve slope, and gust speed. Note that this definition is inherently different from the one used in the ECR, where the term intensity refers to the subjective intensity level as reported in an ECR occurrence report by the flight crew. The treatment of the *Nz* signal and its role in the detection of turbulent events is described in Sections 4.2.3 and 4.2.4, while the calculation of intensity level from the signal is described in Section 4.2.5.
- ***Nz* signal (raw vs. filtered)** – Throughout this section, the term *Nz signal* refers to the processed aircraft's Z-axis acceleration signal. The processing applied to the raw *Nz* signal is described in Sections 4.2.3 and 4.2.4. The filtered signal is centred at zero and excludes the low-frequency components corresponding to manoeuvres due to the application of a high-pass filter. When characteristics of the unfiltered *Nz* signal is used, this is explicitly stated using the term *raw Nz* signal.
- ***Nz* range** – This term refers to the difference between the minimum and maximum values of the filtered *Nz* signal within the duration of an event or episode.
- **Number of oscillations** – Refers to the total number of complete cycles in the *Nz* signal, calculated by dividing the number of zero-crossings by two. Each complete cycle consists of two consecutive zero-crossings.
- **Frequency** – Refers to the number of oscillations within a specific time period divided by its duration. Frequency is calculated at the event level (number of oscillations divided by event duration) and then aggregated at the episode level as the average frequency across the constituent events for any given episode. This distinction is important because episodes may include intervals with little or no oscillatory activity, separated by quiescent periods; computing frequency directly over the entire episode duration would therefore bias the estimation and yield misleading values.

4.2.2. Data processing

Prior to performing the turbulence analysis, several data preprocessing steps were applied to the recorded flight data in order to ensure data reliability, to exclude non-representative flights, and to improve the robustness of the final results. These preprocessing steps are designed to guarantee that only valid operational flights with trustworthy sensor data are considered within the study. The following preprocessing steps were applied:

- **Removal of potential test flights.** Within the available recorded flight data, certain flights may correspond to maintenance or test flights rather than normal commercial flight operations. These flights are identified and excluded when the departure and arrival airports are the same.
- **Selection of flights starting on ground.** Only flights with an initial state indicating the aircraft is on the ground are retained, ensuring that the full operational sequence of the flight is captured from the beginning.
- **Selection of flights ending on ground.** Similarly, only flights that terminate with the aircraft on the ground are retained, ensuring the flight record is complete and representative of a full flight cycle from take-off until landing.
- **Verification of airborne phase.** Flights are required to contain at least one airborne phase. This filter excludes incomplete or abnormal records corresponding to flights that, for any reason, never became airborne.
- **Validation of availability of required parameters.** Only flights containing the complete set of parameters required for the current turbulence study are retained, ensuring that all subsequent analyses can be performed consistently across the dataset.

Figure 10 below shows the number of flights after each of the preprocessing steps mentioned above.

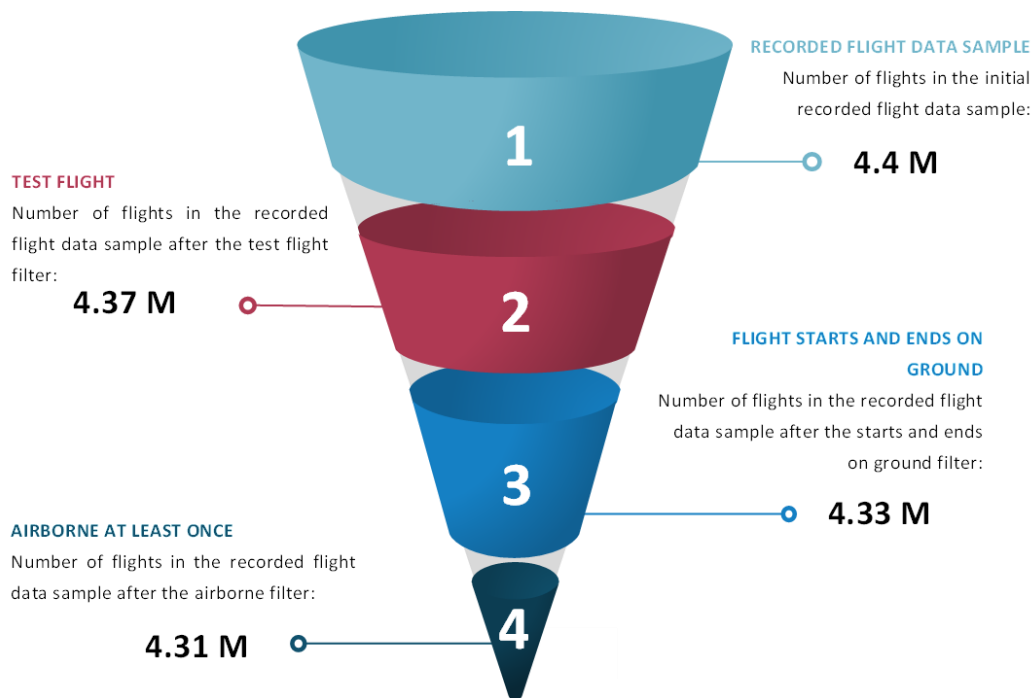


Figure 10 - Number of flights after each preprocessing step of the recorded flight data

4.2.3. Bias correction in vertical accelerometer readings

The second step of the data preprocessing pipeline consists of correcting potential biases in vertical accelerometer measurements. Since the identification of turbulence events within recorded flight data is primarily based on the analysis of acceleration signals, particularly vertical acceleration, ensuring the reliability of these measurements is a critical prerequisite for the study. In addition to vertical acceleration, longitudinal and lateral acceleration measurements are also considered within this correction process. Due to sensor imperfections and other sources of measurement noise commonly present in-flight data recordings, accelerometer data may exhibit a near-constant offset between the recorded acceleration and the expected physical acceleration. This systematic deviation is referred to as sensor bias. Figure 11 shows the bias in vertical acceleration for an example flight. Bias correction is therefore applied as a preprocessing step prior to the identification of turbulence events. The objective of this correction is to reduce false positive detections that may arise when biased acceleration signals are processed by the turbulence identification algorithm.

The methodology used for bias estimation is based on the following principles:

- Acceleration reference convention.** A reference convention is assumed in the Earth-centred frame of reference, where vertical acceleration should have a mean value of 1 g, while longitudinal and lateral accelerations should have a mean value of 0 g. Under ideal static conditions, any persistent deviation from these expected values is considered to represent sensor bias.

- **Bias estimation under quasi-static conditions.** Under the assumption that sensor bias remains approximately constant throughout the flight, mean acceleration values are calculated during flight phases that can reasonably be considered quasi-static. These recorded accelerations are projected into the Earth-centred frame of reference using the appropriate rotation matrix.
- **Identification of quasi-static flight phases.** The following flight conditions are used to identify stable periods suitable for bias estimation:
 - Stabilised level cruise, sustained for at least 2 minutes, defined as:
 - Air/Ground switch signal = 1 (aircraft is airborne)
 - Roll attitude within $\pm 3^\circ$
 - Vertical speed within ± 200 ft/min
 - Pressure altitude variation < 100 ft
 - Computed airspeed variation < 2 kt
 - For flights where no suitable stabilised cruise segment is identified, an alternative estimation is performed during low-speed taxi conditions, defined as:
 - Air/Ground switch signal = 0 (aircraft on ground)
 - Ground speed < 0.5 kt, sustained for at least 1 minute



Figure 11 - Illustration of the bias in the vertical acceleration parameter for a flight. Grey band corresponds to the window in which flight is considered stable

Once these stable periods are identified, the mean measured accelerations are compared against their expected reference values (1 g for vertical acceleration and 0 g for longitudinal and lateral acceleration). Any systematic deviation is identified as sensor bias and subsequently used to correct acceleration measurements across the entire flight.

4.2.4. Identification of turbulent events using recorded flight data

The identification of in-flight turbulence events within flight data is based on the analysis of aircraft acceleration measurements recorded throughout the flight. In particular, the methodology developed in the current study relies on the Root Mean Square (RMS) of vertical acceleration (Nz) over a moving time window, following methodologies previously proposed in airborne turbulence detection research for quantifying aircraft response to atmospheric disturbances [6] [7]. Below are presented the steps of the

turbulence identification methodology. The methodological limitations and associated considerations are discussed in Section 7.2.

Signal Preprocessing and Removal of Low-Frequency Aircraft Manoeuvres:

Prior to turbulence identification, the vertical acceleration signal is processed using a high-pass filter. Specifically, a second order high pass filter is applied via double moving average subtraction. The objective of this filtering step is to remove low-frequency components of the acceleration signal, which are generally associated with pilot-induced aircraft manoeuvres, long-period aircraft dynamics, or gradual flight path changes. Figure 12 illustrates the underlying principle behind this approach. In general, turbulence events and aircraft manoeuvres generate acceleration variations at different characteristic frequencies. Turbulence events are typically associated with relatively high-frequency oscillations, whereas pilot-induced manoeuvres generally produce smoother and more gradual variations in the acceleration signal, corresponding to lower-frequency components.

By leveraging this difference in frequency content, the application of a high-pass filter enables the attenuation of manoeuvre-related accelerations prior to turbulence detection, eliminating the need for a dedicated manoeuvre discrimination algorithm based on additional flight parameters. The selection of the filter cutoff frequency is therefore a critical parameter, as it directly influences the balance between effectively removing manoeuvre-induced accelerations while preserving a genuine turbulence-related aircraft response. To determine an appropriate cutoff frequency, an analysis of the typical frequency ranges associated with both turbulence events and aircraft manoeuvres was performed.

Based on this analysis, a cutoff frequency of 0.25 Hz was selected as the most suitable compromise for the current study. This value effectively removes low-frequency oscillations associated with aircraft manoeuvres while preserving higher-frequency fluctuations characteristic of turbulence events. In practice, this corresponds to filtering out acceleration oscillations with periods greater than 4 seconds.

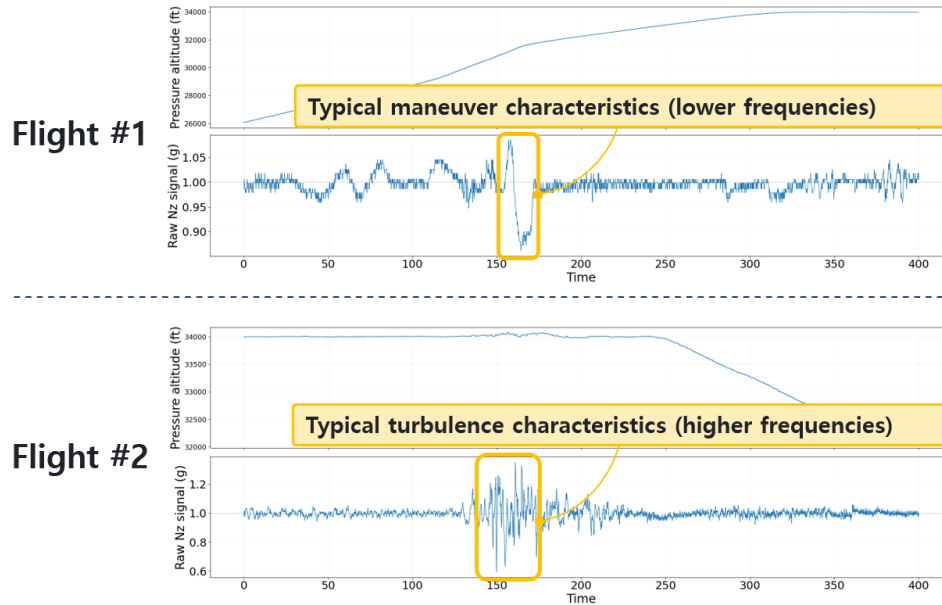


Figure 12 - Typical behaviour in the vertical acceleration parameter (Nz) in two different scenarios: manoeuvre (Flight #1), and turbulence (Flight #2)

Root Mean Square (RMS) of the Vertical Acceleration

After signal preprocessing, the intensity of the aircraft response to the turbulence intensity is quantified through the calculation of the Root Mean Square (RMS) of the filtered vertical acceleration signal. The RMS value is computed using a 5-second moving window, according to:

$$RMSg = \sqrt{\frac{1}{N} \sum_{i=1}^N a_i^2}$$

where (a_i) corresponds to the high-pass filtered vertical acceleration measurement, and N the total number of data samples within the 5 second window. The RMS approach provides a measure of the energy content of short-duration acceleration fluctuations and has been widely used in previous turbulence detection methodologies, particularly in certification-oriented research and flight test analysis [7]. Note that the use of $RMSg$ does not compute the intensity of the incoming atmospheric turbulence itself, but rather the intensity of the aircraft's response to that turbulence, which may vary depending on aircraft mass, aerodynamic configuration, airspeed, altitude, and structural and dynamic properties. This is discussed in more detail in Section 7.2, where limitations of the identification methodology applied to the recorded flight data are discussed.

4.2.5. Calculation of intensity level

Detected turbulence events are classified according to RMS-based intensity thresholds adapted from the methodology proposed by [6]. For the current study, a minor adaptation of the turbulence intensity thresholds proposed in the reference methodology [6] has been introduced. An additional lower threshold of $RMS = 0.1$ has been incorporated as the minimum criterion for classifying a turbulence event as light turbulence in order to reduce the identification of low-magnitude acceleration fluctuations that may not necessarily correspond to meaningful atmospheric turbulence events. Unlike the methodology described in [6], which was developed in the context of turbulence detection system certification under controlled conditions, the present study applies the methodology to a broader range of operational flights from multiple airlines, aircraft types, and flight conditions. As a result, the recorded acceleration data may contain residual signal variations caused by sensor noise, aircraft-specific characteristics, operational variability, or non-turbulence-related aircraft dynamics. Table 4 below shows the thresholds used for determining the turbulence intensity of an event.

Table 4 - RMS of vertical acceleration bounds for categorising turbulence intensities⁵

Turbulence Intensity	RMSg Lower Bound	RMSg Upper Bound
Null	0	0.1
Light	0.1	0.2
Moderate	0.2	0.3
Severe	0.3	Unbounded

These thresholds allow the classification of turbulence events according to increasing levels of aircraft dynamic excitation while maintaining consistency with thresholds previously adopted in turbulence detection research. In addition, the qualitative turbulence intensity categories are aligned with those defined in the ECCAIRS2 taxonomy in the ECR, ensuring methodological consistency across the different components of the present study. Once the RMS of the vertical acceleration signal has been computed, the start and end points of individual turbulence events are determined by analysing the evolution of the RMS signal around each detected peak. For each identified RMS peak, the event boundaries are defined as the points at which the RMS value falls below the following threshold:

$$Thresholds = \min(50\% \text{ Peak}_{RMS}, 0.1)$$

This dynamic thresholding criterion allows the identification of turbulence events whose duration better captures the build-up and decay phase surrounding the maximum turbulence intensity. Compared with the use of fixed RMS thresholds to identify the start and end point of a turbulence event, this approach improves the representation of longer-duration turbulence events while avoiding excessive fragmentation of a single physical event into multiple detections.

⁵ Lower bounds are inclusive.

The selected criterion was established through an iterative calibration process based on the analysis of representative flight segments, with the objective of balancing detection sensitivity and event consistency. Different approaches were evaluated, including the use of a fixed threshold of $RMS = 0.1$ and a threshold defined as 50% of the event peak value. A purely relative threshold based on 50% of the peak intensity was found to better capture the gradual onset and dissipation of turbulence events. However, for high-intensity events, this criterion alone could result in event boundaries being defined at RMS values significantly higher than 0.1, thereby excluding portions of the turbulence event that would still be classified as light turbulence according to the adopted intensity thresholds. For this reason, the final criterion combines both approaches by defining the event boundary using the minimum of 50% of the peak RMS value and $RMS = 0.1$.

This ensures that the complete development of the turbulence event is captured, including its build-up and decay phases, while maintaining consistency with the turbulence intensity classification scheme. Figure 13 below compares the two initial threshold definitions evaluated for determining turbulence event boundaries and illustrates the rationale behind the final criterion adopted. The Figure shows a fixed threshold of $RMS = 0.1$ (green) and a dynamic threshold corresponding to 50% of the event peak RMS value (red). The upper plot shows the aircraft altitude profile, while the lower plot shows the RMS of the N_z signal.

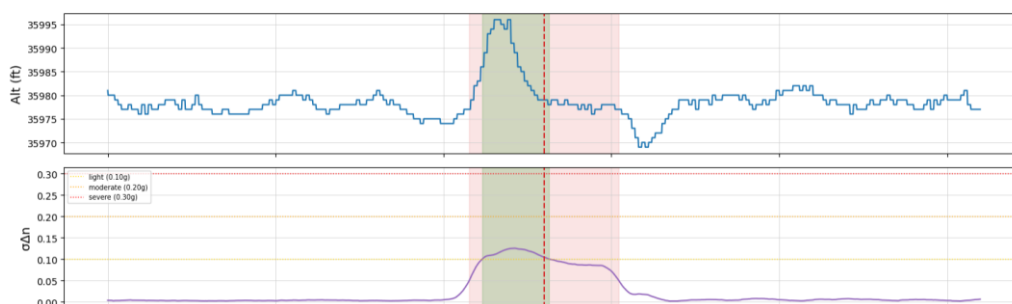


Figure 13 - Illustration of two initial criteria evaluated for determining the start and end of turbulence events

4.2.6. Aggregation of turbulence events into episodes

Individual turbulence events represent discrete threshold exceedances within a flight. In practice, a turbulent episode often manifests as a series of closely spaced (in time) turbulence events rather than a single isolated event. To better reflect the operational nature of a turbulence episode, individual turbulence events are grouped into so called turbulence episodes. An episode is defined as a sequence of consecutive turbulence events within the same flight where the time elapsed between the end of one event and the start of the next does not exceed 5 minutes. If this gap is exceeded, the episode is considered closed, and a new one begins with the subsequent turbulence event. This aggregation logic is illustrated in Figure 14, which shows an example of multiple turbulence events and their grouping into episodes based on the inter-event time gap Δt . The upper plot in the Figure shows the aircraft altitude profile, while the lower plot presents the RMS of the N_z signal, illustrating how individual turbulence events are identified and

subsequently grouped into a common episode. Events separated by less than 5 minutes ($\Delta t < 5 \text{ min}$) are considered part of the same turbulence episode. The 5-minute threshold was selected based on operational considerations and the iterative review of representative flight segments. It is sufficiently long to capture intermittent turbulence encounters as part of the same episode, while remaining short enough to avoid merging operationally distinct turbulence events separated by sustained periods of smooth flight.

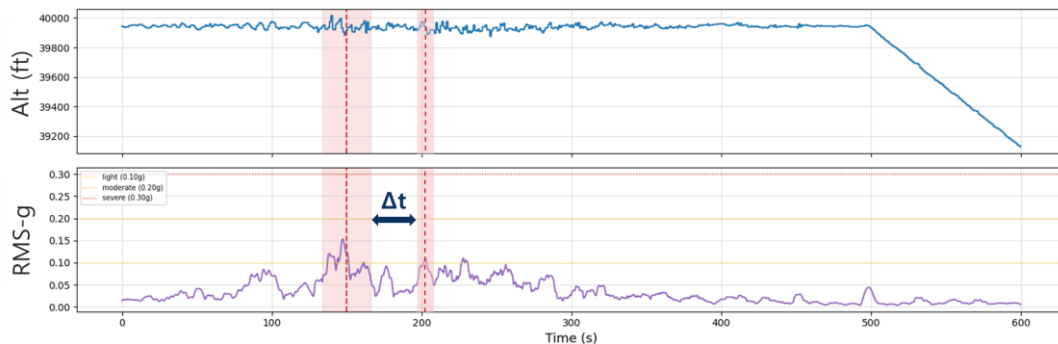


Figure 14 - Illustration of various turbulence events, separated by a difference in time Δt

4.2.7. Identification of flight phase for turbulence episodes

The final step in the identification methodology is to assign each detected turbulence episode to the flight phase in which it occurs. This is done using the midpoint between its start and end timestamps. This midpoint was compared with flight-specific markers derived from the series of parameters available in the recorded flight data, namely the air/ground status, altitude, airport elevation, and aircraft position. The phases relevant to this study are initial climb, climb, cruise, descent and approach. Ground, take-off, final approach and landing were additionally identified to define the complete flight sequence. Where the required markers were unavailable, the phase was classified as unknown. Table 5 summarises the criteria and thresholds used to assign a flight phase to each detected turbulence episode.

Table 5 – Flight phase classification criteria applied to turbulence episodes

Flight phase	Air/ground status	Height above origin (HAO)	Pressure altitude	Height above touchdown (HAT)	Additional criterion
Ground	Ground	—	—	—	Before take-off or after landing
Take-off	Air	Take-off to 1,000 ft	—	—	Begins at the first ground-to-air transition
Initial climb	Air	1,000–3,000 ft	—	—	Between the first upward crossings of 1,000 and 3,000 ft
Climb	Air	Above 3,000 ft	—	—	From 3,000 ft to the top of climb

Cruise	Air	—	—	—	Between the top of climb and top of descent
Descent	Air	—	Above 3,000 ft	—	From the top of descent to the final downward crossing of 3,000 ft
Approach	Air	—	From 3,000 ft	To 1,500 ft	Between the final crossings of the two thresholds
Final approach	Air	—	—	Below 1,500 ft	From 1,500 ft to touchdown
Landing	Ground	—	—	—	Begins at the final air-to-ground transition

The top of climb and top of descent were determined from the altitude profile rather than by applying fixed altitude values, allowing the method to accommodate differences in cruise altitude and operational profiles. The top of climb was derived within 200 NM of the origin and, where possible, placed at the beginning of a stable level segment close to the maximum altitude. The top of descent was identified within 200 NM of the destination as the last point at which the aircraft remained close to its maximum height before beginning the arrival descent.

Initial climb was defined as the band between 1,000 and 3,000 ft above the origin, while approach was defined from the final descent through 3,000 ft pressure altitude to 1,500 ft above touchdown. Using height relative to the origin or touchdown, where applicable, accounts for differences in airport elevation. These boundaries exclude the portions of flight immediately after take-off and before touchdown, where measured accelerations may be influenced by terrain-induced airflow or wake turbulence from other aircraft. This distinction is particularly important because flight data records the aircraft response but does not identify the turbulence type or source; the thresholds therefore reduce the likelihood of including turbulence mechanisms outside the scope of the study.

5 CHARACTERISATION OF TURBULENCE ENCOUNTERS

This chapter presents the principal findings of the study related to the characterisation of turbulence encounters, derived from a detailed characterisation exercise performed across the two data sources (ECR data and recorded flight data), as discussed in Chapter 2.

5.1. Preliminary considerations

5.1.1. Data sources and their complementarity

The findings presented in this chapter are drawn from the combined analysis of the two key data sources of this study, namely ECR data and recorded flight data. This section briefly describes some key characteristics of the two data sources and the relevant differences between them that should be kept in mind when interpreting the results.

Firstly, the ECR data is influenced by mandatory and self-reporting biases. Under Regulation (EU) No 376/2014, an occurrence is reportable to the ECR when it leads to a safety issue. Mandatory reporting therefore applies to occurrences which may represent a significant risk to aviation safety. As a result, turbulence encounters would therefore be reportable when they result in, or have the potential to result in, a significant safety risk (e.g. injury, damage). In fact, the existing regulatory framework requires reporting of “severe turbulence encounter or any encounter resulting in injury to occupants or deemed to require a ‘turbulence check’ of the aircraft”. Consequently, the frequency of ECR-based Safety Performance Indicators is a frequency based on reported occurrences and not representative of turbulence encounters as a whole.

The recorded flight data, by contrast, covers a large sample of flights irrespective of whether or not turbulence occurred. It is assumed that this data set yields the actual or true frequency of turbulence encounters, although taking into account the limitations of the turbulence identification methodology. The recorded flight data, however, holds no records of for example aircraft damage or injuries as a consequence of the turbulence encounters.

The two datasets therefore offer two different, yet complementary, views on the same topic. The recorded flight data provides an objective estimate of the frequency of turbulence encounters, while the ECR data contains information on what happened before, during and after the reported turbulence encounters (e.g. damage, injuries, measures taken by the flight crew). In conclusion, the recorded flight data may represent the rate of physical encounters with turbulence (within the limitations of the turbulence identification methodology used in the present study, discussed in Section 4.2), whereas the ECR data is generally biased towards events with consequences (since, by definition, those are events which are reportable to the ECR) but may provide operational context.

A second point to consider is the fact that the notion of *turbulence intensity* (generally referred to as intensity level) has a different meaning in the two datasets. In neither case does the term intensity refer to the intensity of the incoming turbulence itself, since that is a characteristic of the atmosphere, distinct from both the crew's perception of the encounter and the aircraft's measured response to it. The two meanings for intensity level used in the ECR data and the recorded flight data are related but not equivalent to each other and should therefore not be compared:

- In the ECR data and analysis, intensity refers to the subjective assessment of the “severity” of the turbulence encounter as perceived by the reporter (e.g. pilot or cabin crew member) and reporting entity (e.g. airline).
- In the analysis of recorded flight data, however, intensity refers to the objective magnitude of the measured aircraft response to turbulence, in terms of g-loads, which depends not only on the intensity of the turbulence but also on aircraft specific and operational parameters such as airspeed, air density, and wing loading, among others.

5.1.2. Treatment of very high severity outliers in the ECR dataset

The ECR dataset contains some very high severity occurrences, defined as those with fatal injuries and/or the destruction of the aircraft (aircraft damage of category “Destroyed”). Over the entire dataset of more than 22,000 turbulence-related ECR occurrences, only four such occurrences have been identified. Their inclusion reflects the worldwide geographical scope adopted for the study, as described in Section 3.2. Although these accidents occurred outside Europe, they were recorded in the ECR following independent EASA investigations.

The four occurrences were manually reviewed and excluded from the main analytical sample because of limitations concerning their operational relevance or the evidence of turbulence involvement. These include non-EU business-aviation operations with limited comparability to the airline operations assessed, and cases where the available investigation information does not establish whether turbulence contributed to the accident or the reported fatality.

These occurrences are briefly discussed here for the sake of completeness and due to their severity, but they are excluded from the analysis. Table 6 records their details and provides external references for the interested reader. The descriptions explain the circumstances and relevance of each occurrence individually; they are not intended to establish a general pattern for very high severity turbulence accidents.

Table 6 - Details of the identified very high severity ECR occurrences

Date	Turbulence type	Intensity level	Damage severity level	Flight phase	Fatal Injuries	External reference
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27/10/2019	Convective Turbulence	Severe	Destroyed	En-Route	None	[8]
21/05/2024	Convective Turbulence	Severe	Minor	En-Route	1 Pax	[9]
05/05/2019	Convective Turbulence	Severe	Destroyed	En-Route	3 Pilots, 10 Pax	[10]
14/12/2017	Unknown	Moderate	Destroyed	Approach	2 Pilots, 1 Pax	[11]

5.2. General characterisation and turbulence observation frequency

Before turbulence occurrences are further examined, it is worth establishing the overall picture that each dataset presents: how often turbulence is reported/measured, how turbulence events are distributed by intensity level, and, drawing from the recorded flight data, the characteristics of the average turbulence episode. This establishes the scale and characteristics of the turbulence encounters discussed in the remainder of the chapter, while introducing two key themes that recur throughout the analysis: the reporting bias in the ECR data and the low intensity turbulence that dominated the turbulence episodes found in the recorded flight data.

5.2.1. Overall turbulence observation frequency

Figure 15 shows the evolution of the total number of occurrence and total turbulence-related ECR occurrences per 1,000 flights. Over the study period the ECR contains over 22,000 turbulence-related occurrences. The percentage share of turbulence-related occurrences with respect to the total number of ECR occurrences is shown in Figure 16.

Figure 15 shows that the frequency of turbulence-related occurrences remains broadly stable until 2022, increases markedly in 2023, and stabilises at the higher level thereafter. The same step is visible in the percentage share with respect to all ECR occurrences shown in Figure 16, with an average of approximately 0.60% before 2023 which rises to approximately 1% from that year on. This trend differs from the gradual and continuous rise in total ECR reported occurrences per 1,000 flights over the same period shown in Figure 15, from 27.68 to 40.40 occurrences per 1,000 flights between 2019 and 2025. This is an indication that the step is specific to turbulence reporting and not part of a general reporting trend.

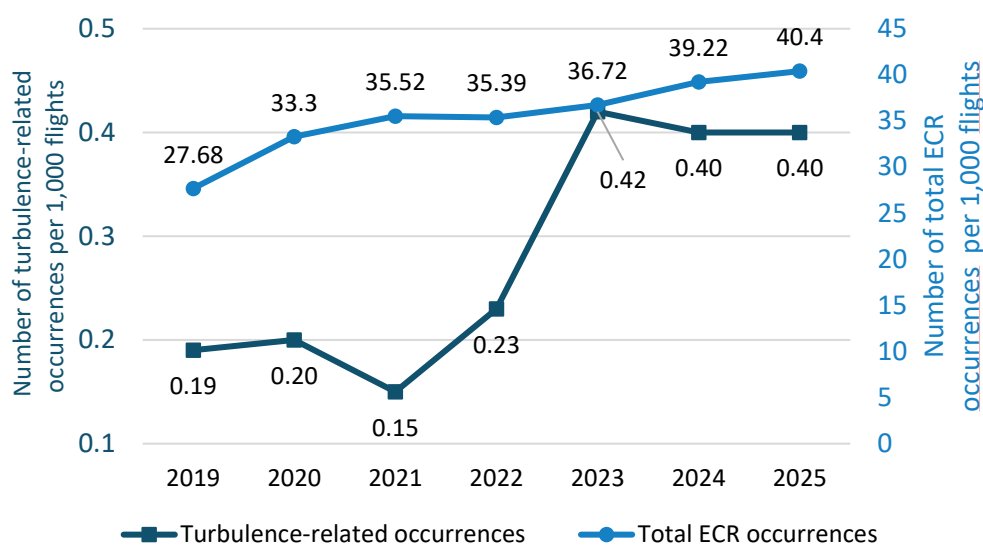


Figure 15 - Evolution of total and turbulence-related ECR occurrences per 1,000 flights

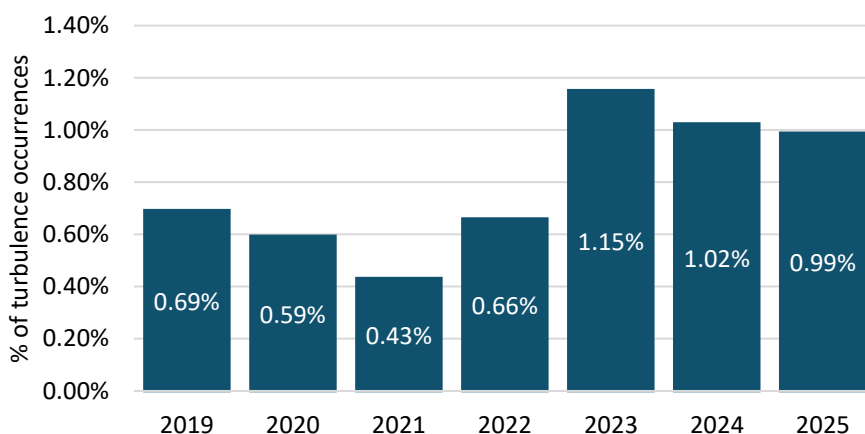


Figure 16 - Evolution of the share of turbulence-related occurrences to total volume of ECR occurrences

The step in 2023 is interpreted as a change in reporting practices rather than a change in the actual occurrence rate of turbulence. Two developments coincide with this change. Firstly, the entry into force of the ERCS risk-scoring requirement in January 2023 under Regulation (EU) 2021/2082 [12], which made the reporting of lower severity encounters more likely. Secondly, a growing awareness of the relevance of turbulence events for aviation safety may also have contributed. In recent years, turbulence has received growing attention from regulators, industry bodies, and operators. The ICAO annual safety report of 2024 identified turbulence as the leading cause of accidents in 2023 [2], while industry initiatives such as IATA's Turbulence Aware platform (aimed at improving turbulence monitoring and mitigation) have expanded with new airlines and data integrators in these past years [13]. Neither development means that there is more turbulence in the air.

The recorded flight data provides the complementary picture. Figure 17 shows that only 17.5% of flights contain at least one turbulence episode. The overall frequency amounts to 197 episodes per 1,000 flights, spread across 175 affected flights per 1,000 flights with an average of 1.13 episodes per affected flight, summarised in Table 7. The average number of episodes per affected flight indicates that a flight subject to turbulence rarely experiences more than a single episode. Figure 18 confirms this directly: across all intensity levels most affected flights contain a single episode, and the proportion falls away rapidly as the number of episodes per affected flight (N) increases. The predominance of flights with a single turbulence episode is slightly stronger at higher intensity, where about one in a hundred flights has more than one moderate or severe turbulence episode, against about one in ten flights for light turbulence. Measured across all flights, turbulence therefore affects a significant portion of flights (approximately 1 in 5) and predominantly does so through a single turbulence episode.

Table 7 - General frequency of turbulence episodes in the recorded flight data

Attribute	Value
Number of turbulence episodes per 1,000 flights	197
Number of flights with turbulence episodes per 1,000 flights	175
Average number of episodes per affected flight	1.13

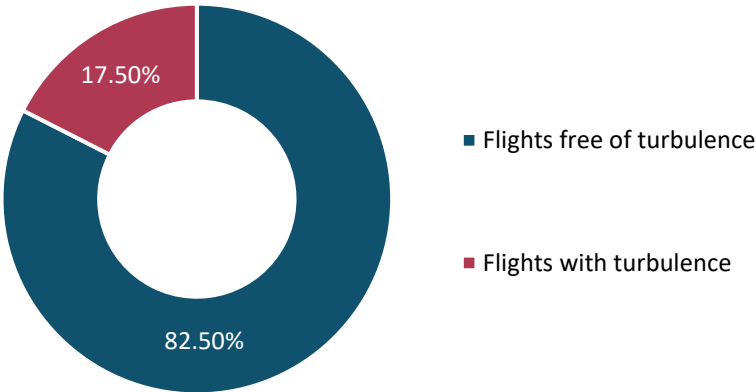


Figure 17 - Percentage of flights with and without turbulence (recorded flight data)

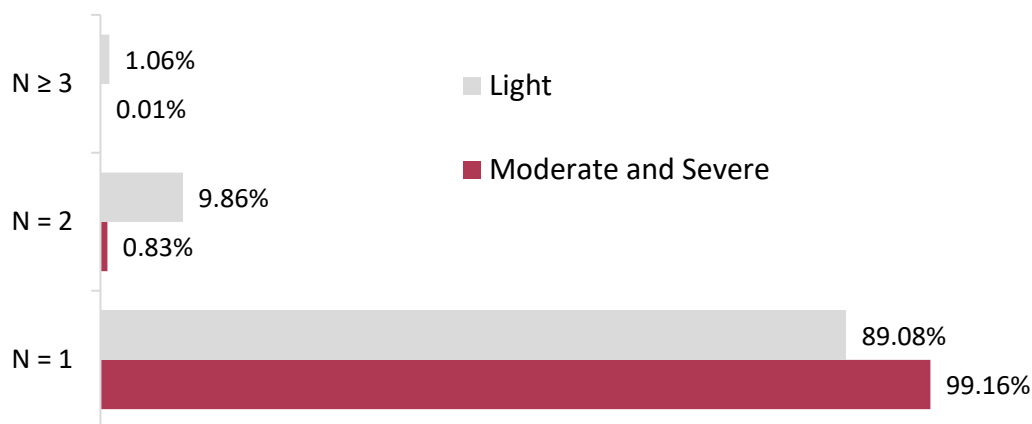


Figure 18 - Distribution of flights by number of turbulence episodes per flight (N), as a percentage⁶ (recorded flight data)

5.2.2. Intensity level

Figure 19 shows the distribution of turbulence-related ECR occurrences by reported intensity for the study period (2019-2025). Intensity is not reported in approximately 41% of the occurrences. Among those with a reported intensity, moderate (26%) and severe (23%) are the two most common categories, while light turbulence accounts for less than 10% of the occurrences.

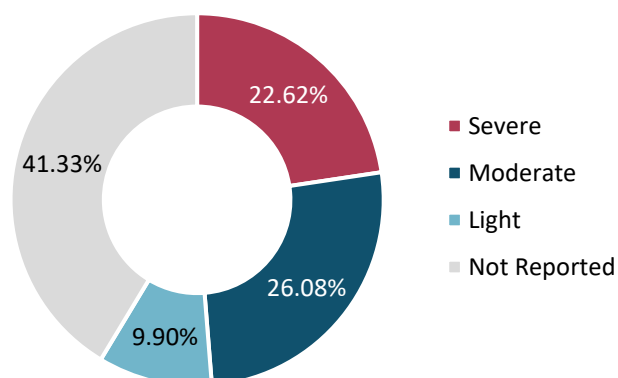


Figure 19 - Share of turbulence-related ECR occurrences by intensity level

Figure 20 shows the breakdown of turbulence episodes in the recorded flight data by intensity level, where intensity definition varies respect the ECR as presented in Section 4.2.1. The results differ significantly from the turbulence-related occurrences in the ECR dataset: the overwhelming majority of turbulence episodes are of light intensity, with less than 3% of the episodes classified as moderate or severe intensity level.

⁶ Percentages in this figure are computed with respect to flights within each intensity level group.

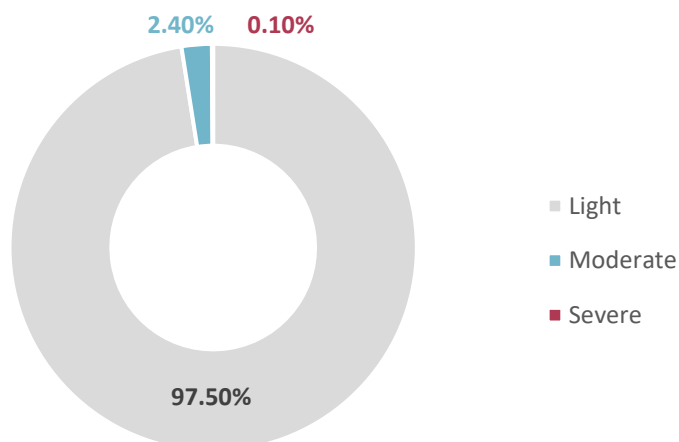


Figure 20 - Breakdown of turbulence episodes by intensity level (recorded flight data)

The difference between the two datasets, and the near parity between light and moderate/severe occurrences in the ECR data sample, are themselves findings that point towards the reporting bias of the ECR. The ECR data sample is, by construction, composed of turbulence encounters that posed a significant enough safety risk to warrant reporting. This effectively translates into a bias towards events with outcomes and consequences, which in turn is generally associated with higher reported turbulence intensity. The recorded flight data, by contrast, is assumed to represent the true physical frequency of turbulence. The intensity distributions from the two sources cannot be compared directly, since they are proportions within their own datasets and, as discussed in Section 4.2.1, the definitions of intensity differ between them: in the recorded flight data, the intensity of an episode is defined by predefined thresholds on the RMS of the Nz signal, applied consistently across the entire volume of data, whereas in the ECR it is the intensity reported by the stakeholder submitting the occurrence, and is therefore qualitative, subjective, and often strongly affected by the presence of consequences, for two reasons. First, because events of higher physical intensity are more likely to cause the outcomes or consequences that warrant reporting to the ECR. And second, because the presence of such consequences is itself likely to bias the reporter towards a subjective perception of higher intensity.

Some conclusions can nonetheless be drawn. The distribution in the recorded flight data of Figure 20 matches what is expected on physical grounds: light turbulence dominates, moderate intensity is far less frequent at approximately 2% of episodes, and severe turbulence is rare, at 0.1%. The distribution of the turbulence-related ECR occurrences is the reverse, weighted towards the higher severity levels. Two features of the ECR distribution are worth noting. Firstly, light occurrences are a minority of the dataset: even if the occurrences with a "Not Reported" intensity are assumed to be light, on the basis that a moderate or severe encounter would generally have had its intensity recorded, the light and unreported occurrences together account for only about half of the turbulence-related ECR occurrences. Secondly, moderate and severe occurrences are of similar frequency, at approximately 20 to 25% each. Both features point clearly to the reporting bias of the ECR. Turbulence encounters of severe intensity are most likely to

be reported as their consequences, which are an important factor for reporting, are generally more severe. Hence, a higher proportion of the severe encounters are reported to the ECR compared to the proportion of moderate and light encounters, some of which are likely to be unreported. The distribution shown in Figure 19 is unlikely to reflect the underlying frequency of encounters; rather, it is likely to be the consequence of the bias towards higher severity occurrences in the ECR.

To compare the two datasets more accurately, the frequency of turbulence encounters by intensity level per 1,000 flights is considered. These exposure-adjusted metrics are shown in Figure 21 for the ECR data sample, as a yearly evolution, and in Table 8 for the recorded flight data, aggregated over the entire dataset. As expected from the discussion above, the light-intensity rates differ markedly between the two sources: the frequency of light episodes in the recorded flight data is of the order of 10^2 per 1,000 flights, whereas the rate of light turbulence occurrences in the ECR is of the order of 10^{-2} per 1,000 flights, oscillating between 0.02 and 0.05, a difference of approximately four orders of magnitude.

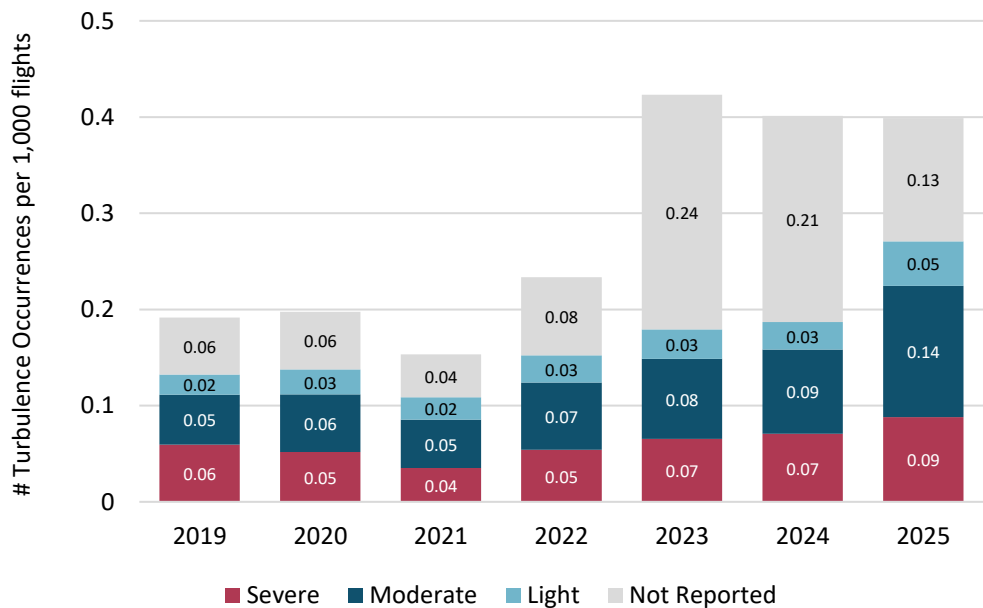


Figure 21 - Evolution of frequency of turbulence-related ECR occurrences, per 1,000 flights, by intensity level

Table 8 – Frequency of turbulence episodes by intensity level, per 1,000 flights (recorded flight data)

Attribute	Value
Number of light turbulence episodes per 1,000 flights	192.52 (order of 10^2)

Number of moderate turbulence episodes per 1,000 flights	4.63 (order of 10^0)
Number of severe turbulence episodes per 1,000 flights	0.24 (order of 10^{-1})

The key finding is how this difference changes as intensity increases. At moderate intensity the rates are much closer, differing by roughly one to two orders of magnitude, at 4.63 per 1,000 flights in the recorded flight data against 0.05 to 0.14 in the ECR. At severe intensity they converge to within, approximately, one order of magnitude, at 0.24 per 1,000 flights in the recorded flight data against 0.05 to 0.09 in the ECR. The agreement between the two datasets therefore improves steadily as intensity rises.

A direct, one-to-one relationship between the two intensity scales cannot, however, be drawn, for the reasons already described above. The narrowing of the gap can be attributed to several factors acting in the same direction. The most likely is that, as physical intensity rises, so does the proportion of encounters that are ultimately reported, since the magnitude of the aircraft response is a primary driver of the injuries, aircraft damage and other consequences that warrant reporting obligations to the ECR. In addition, an encounter of low physical intensity may be reported as moderate or severe because of the subjective biases described above (such as due to the presence of injuries, for example). Finally, different stakeholders will not report an encounter of a given physical intensity at the same reported intensity. The exact contribution of each of these factors cannot be isolated from the data.

What can be stated with confidence is the direction of the effect, and it is this that constitutes the main finding. The gap between physical and reported exposure closes as intensity rises, which indicates that the two intensity constructs, though defined in entirely different ways and not relatable on an event-by-event basis, increasingly reflect the same underlying physical reality as intensity increases. At light intensity the reported picture is governed almost entirely by reporting behaviour and bears little relation to physical exposure, whereas at higher intensity the reported and physical exposure curves draw together, even if the correspondence between an individual reported intensity and a physical one remains uncertain. Severe turbulence is therefore the one regime in which the ECR can be read as informative about the order of magnitude of physical exposure, and it is the regime in which the two independent datasets most nearly corroborate one another.

At severe intensity, and subject to all the biases already noted, the data available for this study place the two exposures at a ratio of between two and four turbulence-related occurrences in the ECR for every ten severe episodes in the recorded flight data. This is the relationship found in the data; however, it should be clearly noted that this metric is *not* a capture rate, and it should *not* be interpreted as 20 to 40% of severe episodes being reported, both because the two intensity scales do not correspond on an event-by-event basis and because encounters of lower physical intensity may be reported as moderate/severe in the ECR due to the aforementioned biases. An exact numerical match between the exposures of the two datasets

would not, in any case, be expected even if the two intensity definitions were perfectly aligned; under Regulation (EU) No 376/2014 mandatory reporting applies only to events that may represent a significant risk to aviation safety, and not every severe turbulence encounter gives rise to such a risk. The ratio should therefore be taken as an indicative measure of the relationship between the two quantities, in the datasets available and with all the stated caveats, rather than as a rate at which severe turbulence is reported.

Finally, the temporal evolution of the breakdown of turbulence-related ECR occurrences by intensity level, in percentage terms, excluding the “Not Reported” category, is shown in Figure 22. For the reported intensity levels, the overall distribution remains approximately stable over time. Consider now the data of Figure 22 and Figure 21 together: the increase in overall frequency after 2023 shown in Figure 15 is driven mostly by occurrences with “Not Reported” intensity (which increases from 0.08 in 2022 to 0.24 in 2023), while the percentage breakdown for reported intensity levels of Figure 22 remains stable during that period.

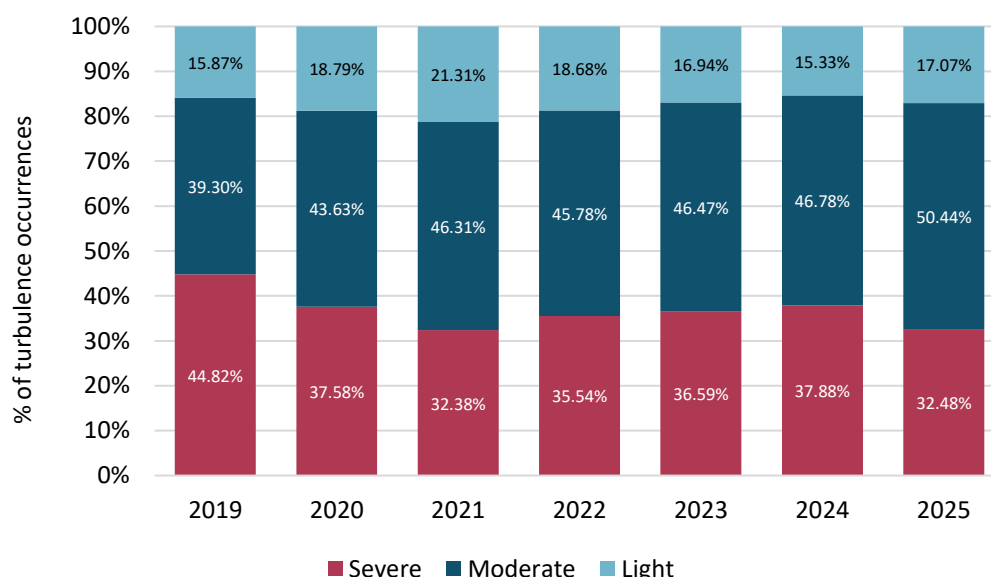


Figure 22 - Evolution of the distribution of turbulence-related ECR occurrences by intensity level (only classified intensity levels, excluding “Not Reported”)

This supports the hypothesis proposed in Section 5.2.1 regarding a possible shift in reporting practices. The increase in reported turbulence occurrences from 2023 is largely attributable to occurrences in which intensity was not specified, and therefore in which the intensity level is likely to have played a limited role in the event. This is consistent with a change in reporting practices that captured less severe events previously left unreported, rather than a genuine change in the rate of turbulence encounters.

5.2.3. Physical structure of a turbulence episode

The recorded flight data reveals the physical characteristics of turbulence encounters, which the ECR data cannot provide as the ECR records an occurrence as a single reported event without actual measurements

of the related turbulence. This section examines the physical structure of turbulence episodes from the available parameters in the recorded flight data.

Table 9 summarises the average duration, Nz range, number of oscillations and number of events of turbulence episodes in the recorded flight data, aggregated across all detected episodes. The average turbulence episode lasts approximately one minute, contains between two and three discrete turbulent events and around 26 vertical-acceleration oscillations, and produces an average Nz range of approximately 0.5 g.

Table 9 - Characterisation of the average turbulence episode

Attribute	Value
Average duration	53.6 s
Average Nz range	0.48 g
Average number of oscillations	25.5
Average number of events	2.4

Episode duration increases with intensity level, as shown in Figure 23. Light episodes last in the order of one minute, whereas moderate and severe episodes last approximately two and a half to three minutes. The analysis shows a roughly threefold increase in duration from light intensity to moderate and severe intensity, whereas the increase in duration between moderate and severe is less significant. The number of events per episode also increases by roughly a factor of three, as shown in Figure 24, from about 2.3 for light episodes to around 7 for moderate and severe intensity episodes.

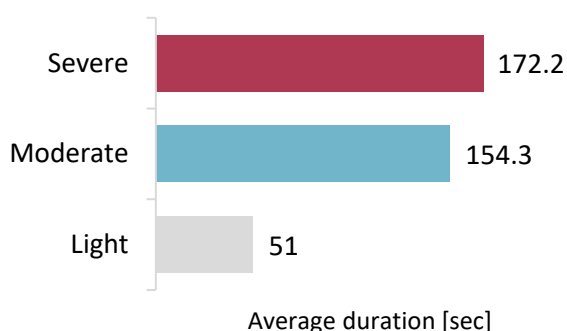


Figure 23 - Average episode duration by intensity (recorded flight data)

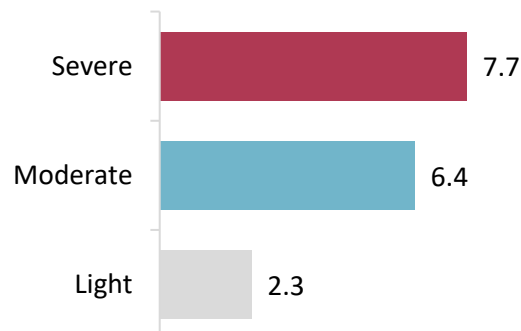


Figure 24 - Average number of events per episode by intensity (recorded flight data)

The average episode duration also increases towards the end of the flight, as shown in Figure 25, for all three intensity levels.

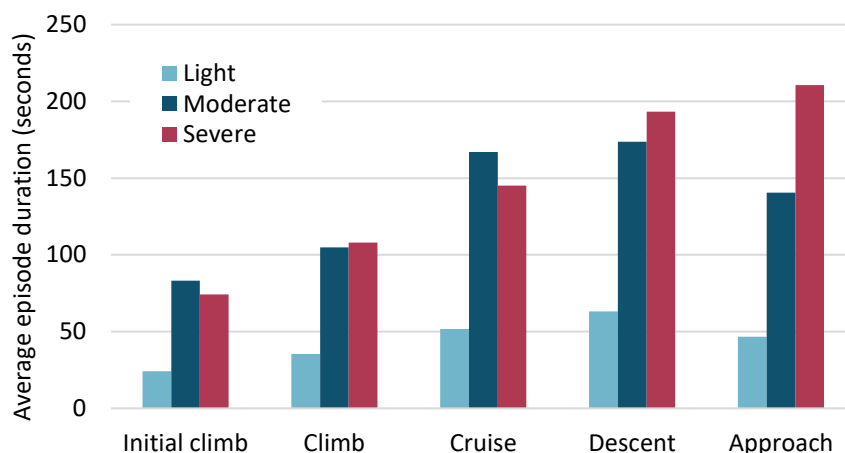


Figure 25 - Average episode duration by flight phase and intensity level (recorded flight data)

The variation of the oscillation frequency across intensity levels is shown in Figure 26. It can be observed that, by contrast to episode duration and the average number of events per episode, the oscillation frequency remains essentially constant across the three intensity levels, with the mean varying only marginally from 0.51 Hz for light episodes to 0.57 Hz for severe episodes. The results indicate that stronger intensity levels (that is, stronger aircraft response to turbulence) is associated with longer-lasting encounters but not with a significant change in the frequency of the underlying oscillations. The oscillation frequency remains approximately constant across intensity levels, whereas the episode duration increases and therefore drives the increase in the average number of events and oscillations.

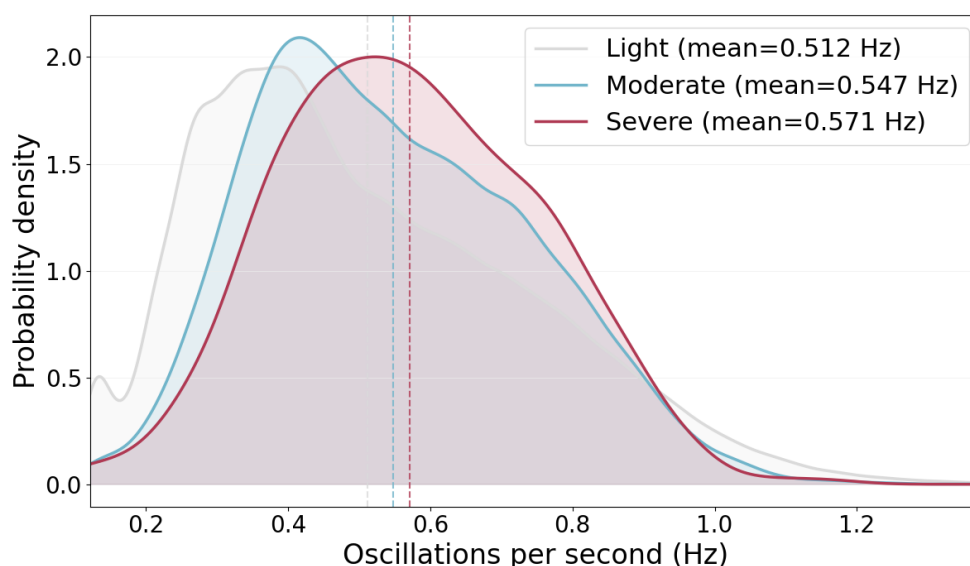


Figure 26 - Probability density of the average episode oscillation frequency by intensity (recorded flight data)

Another property of turbulence concerns the homogeneity of the population of turbulence episodes, in terms of their episode duration, across intensity levels. To explore this in more detail, Figure 27 shows the probability density of episode duration by intensity level. The dispersion of one episode's duration increases with intensity level. Turbulence encounters resulting in a light intensity aircraft response are relatively short-lived and constant in duration, whereas moderate and severe intensity aircraft responses have a wider range, from brief but strong encounters to prolonged ones. The dispersion of the N_z signal range increases with intensity level as well. However, this widening is at least partly inherent to the intensity classification since it is based on the N_z signal itself, whereas the duration is independent of the intensity level classification. This suggests that higher intensity episodes form a less homogeneous population than light intensity episodes.

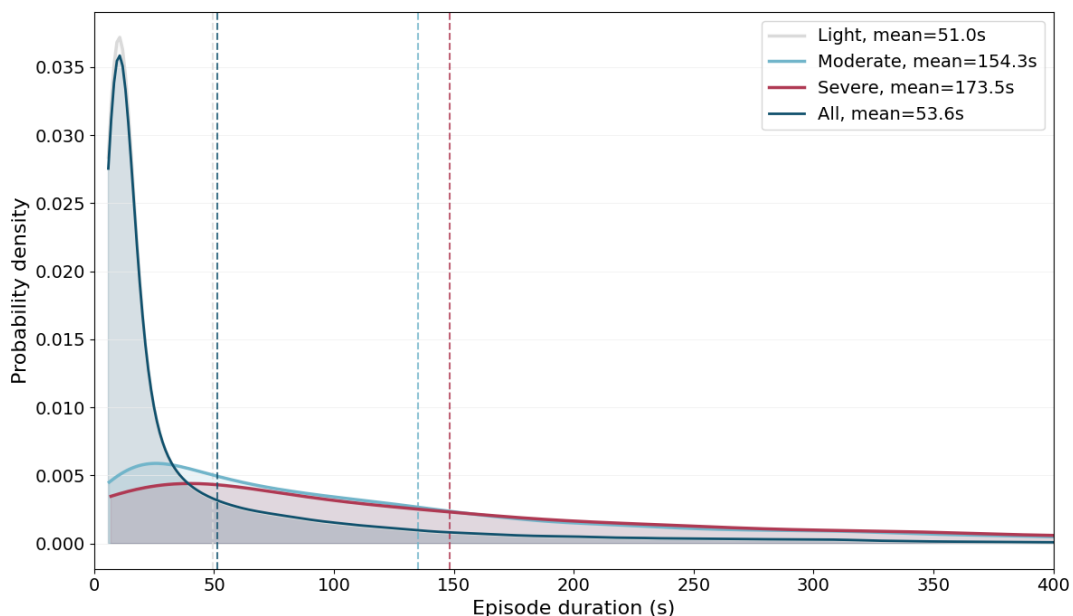


Figure 27 - Probability density of episode duration by intensity

Finally, it can be concluded that most episodes are shorter than the average, while a small number of prolonged turbulence encounters raise the mean (the probability distributions have long tails of prolonged encounters, particularly so for moderate and severe intensity).

Additional details on the variation of the key parameters discussed in this section with respect to intensity level and flight phase are presented in Appendix C.1.

5.3. Altitude and flight phase

Following the general characterisation of turbulence encounters and their physical structure provided in Section 5.2, this section continues with an analysis of two key parameters from an operational perspective which are analysed together due to their close relationship, namely flight phase and altitude, discussed in

Sections 5.3.1 and 5.3.2 respectively. Additionally, Section 5.3.3 presents an interesting finding related to the concentration of turbulence episodes near the end of the cruise phase and its relationship with onboard weather radar technology.

5.3.1. Flight phase

Figure 28 shows the distribution of turbulence episodes by flight phase in the recorded flight data. The episodes are unevenly distributed. Descent holds the largest share (45%) and approach the second largest (23%). Cruise accounts for less than 10% of all turbulence episodes, with the remainder split between climb and initial climb.

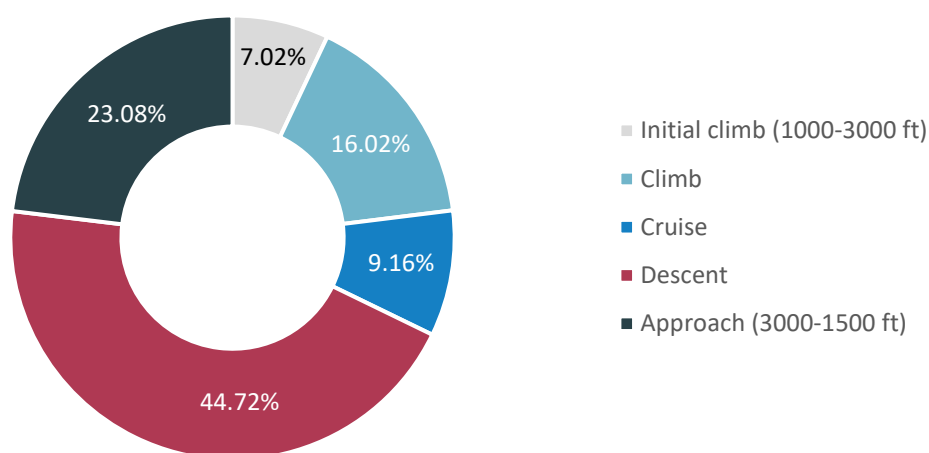


Figure 28 - Breakdown of turbulence episodes by flight phase (recorded flight data)

To adequately analyse the data shown in Figure 28, Figure 29 shows the average duration of each flight phase. Cruise is the longest phase and lasts approximately one hour, while descent and approach combined have an average duration of approximately 25 minutes. The average duration of cruise of approximately one hour (which may seem short) is largely driven by the fact that the vast majority of flights in the recorded flight data are short-haul operations (99%, see Section 3.1.2). Despite the bias of the recorded flight data towards short-haul operations, cruise remains the longest flight phase by average duration in the dataset.

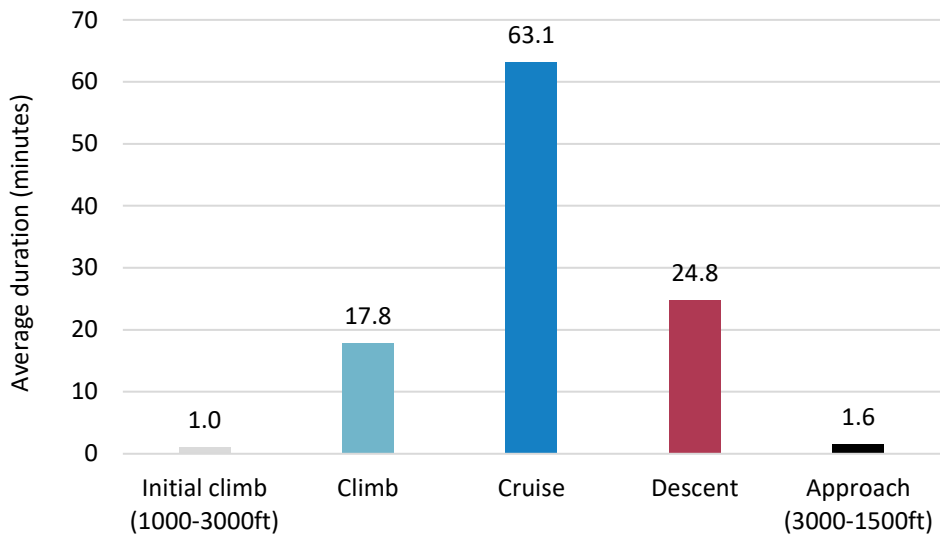


Figure 29 - Average flight phase duration, in minutes (recorded flight data)

The large proportion of turbulence episodes in descent and approach in Figure 28, as well as the minority of episodes in the cruise phase, are particularly striking findings considering that the data is not normalised by the duration of each flight phase. While cruise is the longest flight phase in the recorded flight data, as shown in Figure 29, the distribution of episodes by flight phase presents a clear skew away from cruise and towards the lower altitude phases, in particular towards descent. When normalising the number of episodes by the average time spent at each flight phase, the skew towards lower altitude becomes even more apparent, as demonstrated by Figure 30. On a per-minute basis, turbulence frequency is clearly concentrated in the lower altitude phases of flight, and in particular towards the end of the flight, rather than during cruise.

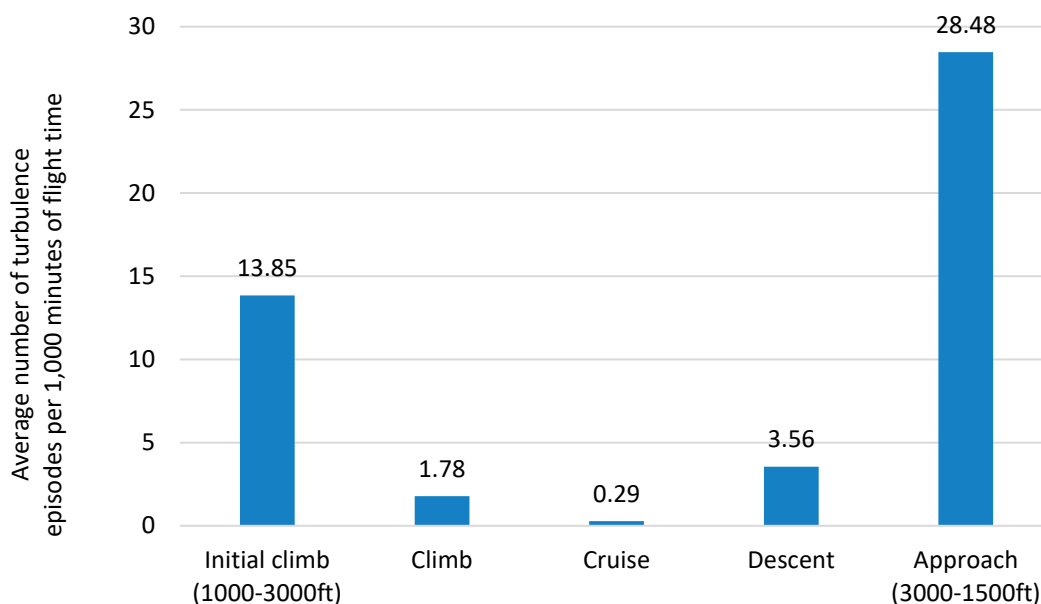


Figure 30 - Distribution of turbulence episodes by flight phase, normalised by 1,000 flight minutes within each phase (recorded flight data)

The concentration of turbulence episodes in the recorded flight data in flight phases at lower altitudes (namely approach, initial climb and descent) is attributed to three factors.

The first set of factors is related to topological and weather-related phenomena, typical of lower altitudes. These distinct low altitude turbulence-generating mechanisms are confined to the lower troposphere because they are products of the atmosphere's coupling to the Earth's surface. Wind flowing over terrain, obstacles, and rough surfaces generates terrain-induced turbulence through friction and flow separation, ranging from small-scale gustiness in the boundary layer to large disturbances in the vicinity of mountain ridges [14]. Daytime surface heating drives convective thermals that rise through the boundary layer, producing turbulent air [15]. A closely related mechanism arises from temperature inversions: nocturnal radiative cooling builds a stable layer that decouples the surface from the winds aloft, and a low-level jet forms just above it, inverting the wind profile (wind speed peaks at the jet core and the shear reverses above it). Although the inversion itself suppresses mixing of airflows, the strong vertical wind shear at its upper boundary becomes a potent, if localized, source of turbulence [16]. Above the boundary layer, the free-atmosphere flow is largely decoupled from surface friction, terrain, and surface heating, so these mechanisms are essentially absent at cruise flight levels. At cruise flight levels turbulence arises instead from jet-stream shear and the Kelvin-Helmholtz instability it triggers, along with breaking gravity waves and convection [17]. Future work should attempt to incorporate weather-related data in the vicinity of airports (e.g. METAR) to assess the influence of local weather conditions on the occurrence of turbulence encounters (see Section 0 for a complete list of recommendations for future work).

The second factor is related to the way in which the magnitude of the aircraft response to turbulence changes throughout the flight. The aircraft response to an incoming turbulent gust is known to increase in proportion to true airspeed and air density and decrease with wing loading. This factor can be broken down into different contributions working together. First, the effect of increased air density makes aircraft more susceptible to incoming turbulence in the lower altitude (higher air density) regime corresponding to initial climb and approach, and to a lesser extent, climb and descent. Second, the wing loading is a factor: as the aircraft weight decreases during the flight so does the wing loading, making the aircraft more susceptible to turbulence. This factor explains the increased number of turbulence episodes detected in the later stages of flight specifically, namely approach and descent, and also explains the increase in average episode duration towards the end of flight observed in Figure 25 (Section 5.2.3). Generally, the lower airspeed flown in descent and approach reduces the aircraft response to turbulence, whereas the higher air density and the lower wing loading due to reduced aircraft weight at the end of a flight both amplify the aircraft response. The concentration of episodes at low altitude in the recorded flight data, and particularly towards the end of flight, suggests that the effect of lower wing loading and higher air density outweigh the influence of reduced airspeed.

The third and final factor is related to the operational flexibility available during cruise. During cruise, the flight crew can generally deviate in altitude or heading to avoid areas of turbulence (both to avoid known areas of convective turbulence detected through on-board weather radar, or to adjust the flight path away from unexpected encounters with clear-air turbulence). On the other hand, during climb, descent and approach, arrival or departure operational procedures and other nearby air traffic may limit the opportunity to avoid areas of turbulence or adjust the flight path.

The distribution of turbulence-related occurrences in the ECR data sample differs significantly from the distribution of turbulence episodes observed in the recorded flight data sample. Figure 31 shows that most turbulence-related ECR occurrences are reported during cruise (around 45%), followed by approach (16%) and descent (12%), while initial climb and climb account for a small portion of turbulence-related ECR occurrences (approximately 8% combined).

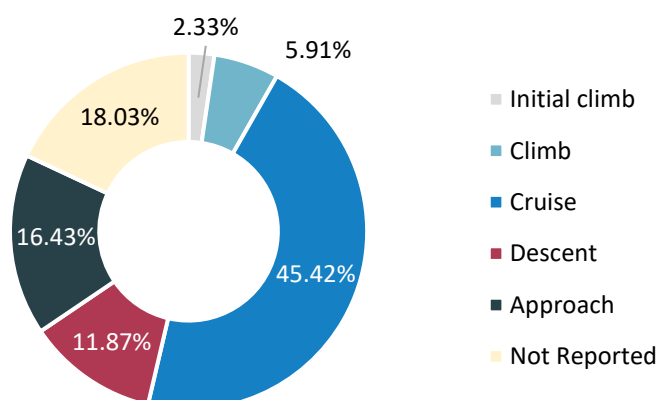


Figure 31 - Distribution of turbulence-related ECR occurrences by flight phase

The dominance of the cruise phase in the distribution of turbulence-related ECR occurrence and its stark contrast with the distribution in the recorded flight data is noteworthy. It is deemed to be a consequence of the combination of three factors, described in detail in the following paragraphs.

The first factor to consider is the difference in the average duration of the cruise phase between the two datasets. Average flight phase duration is not available directly in the ECR data sample, but the ECR turbulence-related data is known to contain a greater proportion of long-haul operations than the set of recorded flight data. As discussed in detail in Section 5.7, the exact split between long-haul and short-haul flights in the recorded flight data cannot be stated because of Data Governance limitations, but long-haul operations represent a very small portion of the recorded flight data. In the ECR turbulence-related dataset, by contrast, the split is approximately 67% short-haul to 33% long-haul operations. The larger share of long-haul flights in the ECR data sample raises the average time spent in cruise, which is at least partly contributing to the higher proportion of turbulence encounters reported in that phase.

A second factor to consider is the reporting bias in the ECR data sample. As introduced in Section 5.2 the ECR is biased towards occurrences with consequences. Figure 32 shows the breakdown of turbulence-related ECR occurrences with a known/recorded flight phase and intensity level. It is observed that cruise has the most severe profile (lowest proportion of occurrences of light intensity), although descent follows closely and the difference relative to the other phases is modest. Cruise is also the only phase in which severe turbulence is reported more often than moderate turbulence. Severe and moderate turbulence result relatively more frequently in injuries, damage and operational consequences, which drives reporting to the ECR. It should be noted, however, that it cannot be determined from the data alone whether this higher intensity in cruise is a result of a higher reporting frequency or reporting bias.

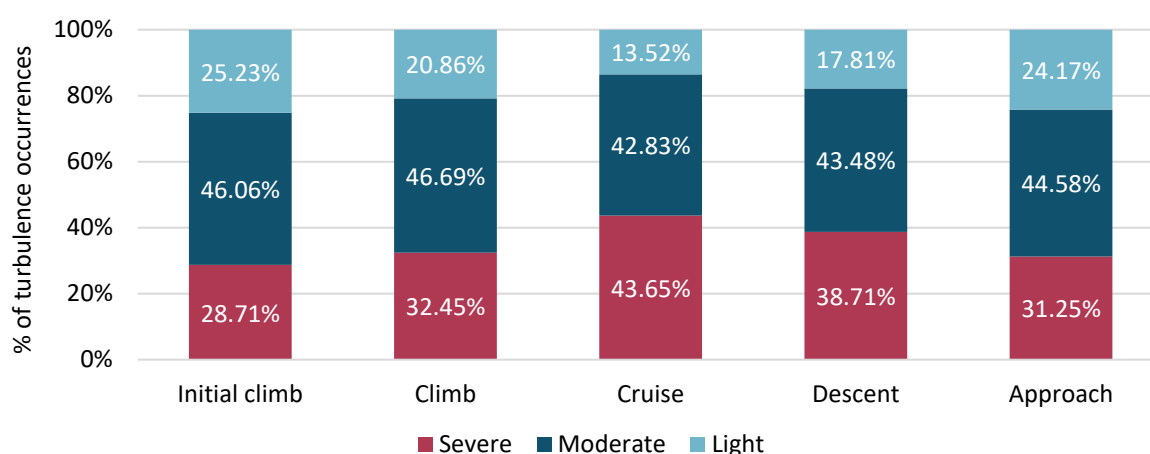


Figure 32 - Distribution of turbulence-related ECR occurrences of known intensity level by flight phase and intensity level

The third factor to consider concerns the way in which cruise differs from the other flight phases. Two differences play a role, the first is type of turbulence and the second is the activity in the cabin. As discussed in detail in Section 5.6, clear-air turbulence occurs predominantly at cruising altitudes and is considerably harder to anticipate than convective turbulence since it is not detectable by conventional on-board weather radar. The second difference is the cabin activity and use of seatbelts. Parts of the cruising phase can be characterised by high activity in the cabin, with passengers and cabin crew more likely to be moving around and unrestrained (walking, standing, using toilet), cabin service taking place, etc. The combination of these two factors is relevant: cruise combines a more active, less restrained cabin with a higher likelihood of encountering unanticipated clear-air turbulence. Taken together these two factors raise the probability of a reportable consequence to the ECR. The role of occupant restraint as a contributing factor in injuries is examined further in Section 5.4.

Taken together, these factors are likely to explain the dominance of cruise in the distribution of turbulence-related ECR occurrences. The concentration of clear-air turbulence at cruising altitudes, the greater cabin activity during cruise, with service in progress and/or occupants more often unbelted, the reporting bias of the ECR towards events with consequences, and the longer average cruise duration arising from the larger share of long-haul operations in the ECR dataset explain why the cruise phase produces the largest share of turbulence-related reports to the ECR, despite being exposed to the lowest amount of turbulence episodes per unit of flight time measured in the recorded flight data (Figure 29).

5.3.2. Altitude

Consider now the distribution of turbulence episodes (in the recorded flight data) and turbulence-related occurrences (in ECR data) by altitude. Due to the close relationship between flight phase and altitudes, the trends observed in the breakdown by flight phase in Section 5.3.1 can also be observed in the altitude breakdown presented hereinafter. Moreover, the analysis by altitude offers additional insights into these observations and sets the stage for further discussions presented in the following sections.

Figure 33 shows the distribution of turbulence episodes by altitude in the recorded flight data. The distribution is bimodal, with a strong peak at lower altitudes and a smaller one at cruising levels, and is clearly skewed towards the lower altitude bands. This is similar to the distribution of turbulence episodes by flight phase, which was skewed towards the flight phases in lower altitude bands. As mentioned in Section 5.3.1, the skew towards lower altitudes is strengthened when normalising the data by the average flight phase duration. The same can be stated here: despite aircraft spending more time at cruising altitudes than in any other altitude band, the distribution of episodes remains clearly skewed towards the lower altitude regime.

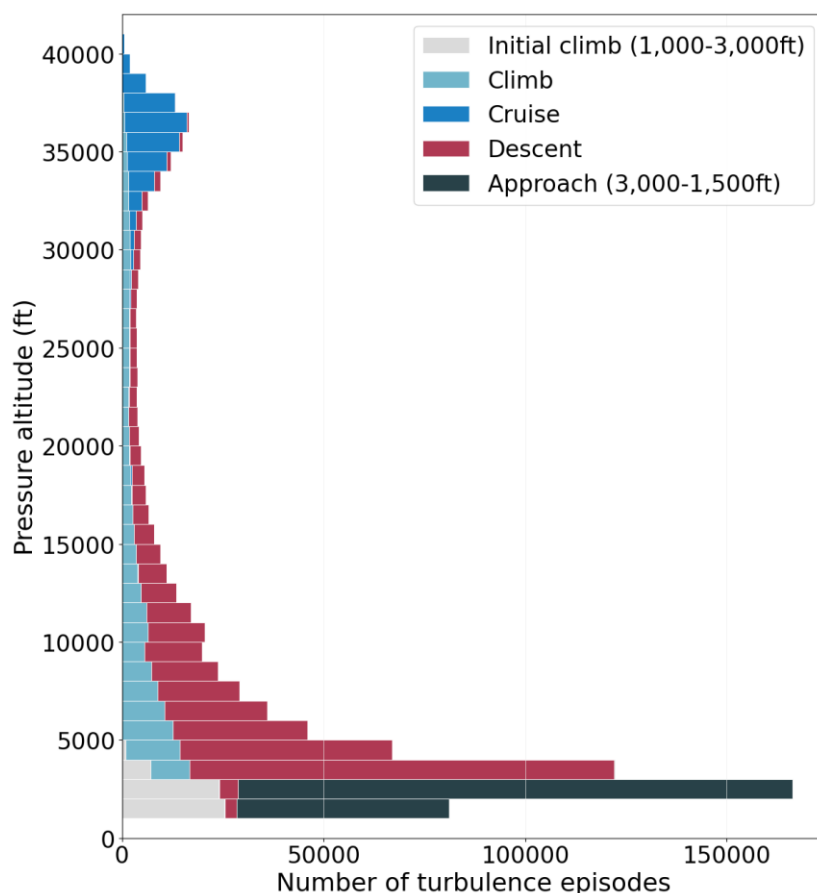


Figure 33 - Distribution of turbulence episodes by altitude and flight phase (recorded flight data, bin size = 1,000 ft)

The bimodal shape observed in Figure 33 does not necessarily correspond to the actual presence or absence of turbulent air at each altitude band. Nevertheless, the bimodal shape of the distribution can be related to two different altitude regimes where turbulence is principally present [18] through different mechanisms. The low-altitude peak coincides with the planetary boundary layer, the lowest part of the atmosphere, where friction over terrain and surface features produces mechanical turbulence, while solar heating of the surface drives convective activity [19]. The secondary peak at cruise levels is consistent with turbulence generated near the tropopause, where the strong vertical and horizontal wind shear on the edges of jet streams is a recognised source of clear-air turbulence, normally above 15,000 ft [20]. This relationship between altitude and turbulence type is explored in more detail in Section 5.6, although it should be noted that unlike the ECR data, the recorded flight data does not measure the type of turbulence and the discussion on type of turbulence presented in Section 5.6 is therefore limited to ECR data only.

Figure 34 shows the altitude distribution of turbulence episodes by intensity level as a probability density function. About 70% of light intensity episodes occur below 10,000 ft, compared to approximately 60% for moderate intensity and about 50% for severe intensity. The data suggests a progressive reduction in the

concentration of episodes at lower altitudes as turbulence intensity increases and it appears that severe turbulence is the least dependent on altitude of the three intensity levels, distributed more evenly across the altitude range. The progressive flattening of the distributions with increasing intensity may indicate that light turbulence is overwhelmingly encountered due to low-altitude boundary-layer phenomena, whereas severe turbulence is driven by localised high-energy triggers (such as turbulence within and near thunderstorms, severe clear-air turbulence or high-altitude wind shear) and widespread across all flight levels.

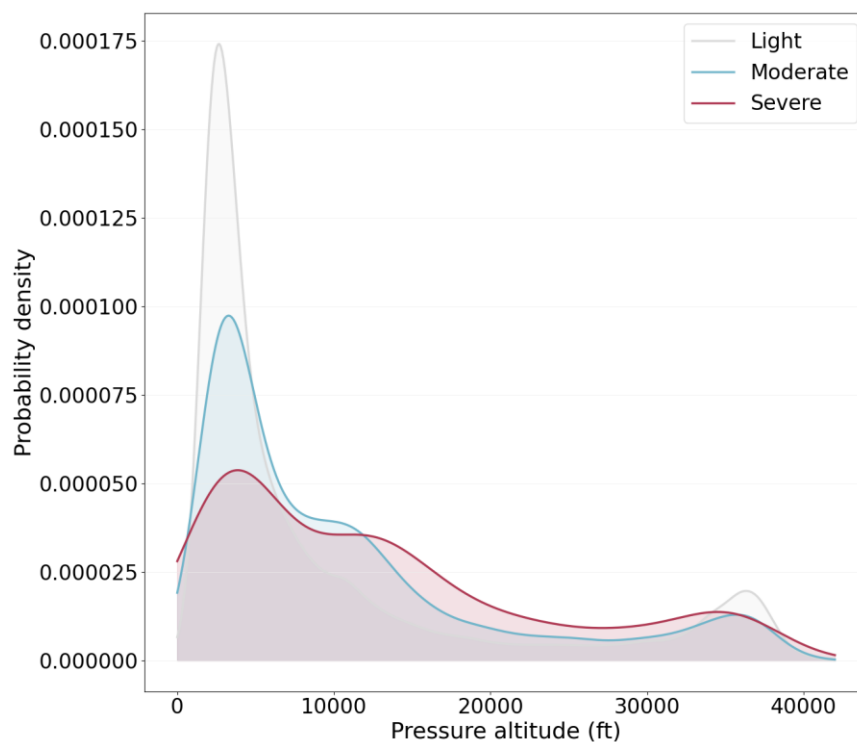


Figure 34 - Probability density of altitude distribution by intensity level (recorded flight data)

The predominance of turbulence at lower altitudes in the recorded flight data has been identified and discussed in detail in Section 5.3.1. Repeating the conclusions here for the sake of clarity, it is deemed to be a consequence of the interplay between meteorological and topology-related phenomena characteristic of the lower altitude regime, the changes to the magnitude of the aircraft's response to incoming turbulent gusts at lower altitudes, and the operational flexibility available during cruise to avoid areas of turbulence.

The altitude distribution of turbulence-related occurrences in the ECR data sample is also bimodal, but its balance between the two peaks differs compared to the results from the recorded flight data. Figure 35 shows the turbulence-related occurrences in the ECR data sample by flight level, with a concentration at cruise levels that is slightly more prominent than the concentration at the lower flight levels. This is in contrast with the results from recorded flight data, where the peak at lower altitude bands clearly dominates, and in agreement with the previous discussion on the distribution by flight phase of Section

5.3.1. While the recorded flight data is skewed towards lower altitudes, the ECR data shows a larger set of turbulence-related occurrences taking place at cruising altitudes. The reasons for this contrast between the two datasets have been identified and explained in detail in Section 5.3.1. The main reasons behind this contrast, repeated here for clarity, are the interplay between the longer average duration of cruise in the ECR dataset due to a larger proportion of long-haul flights, the reporting bias in the ECR data towards events with consequences, the presence of clear-air turbulence at cruising altitudes with its associated difficulty for detection and avoidance, and the increased cabin activity and likelihood of occupants and cabin crew being unrestrained during cruise.

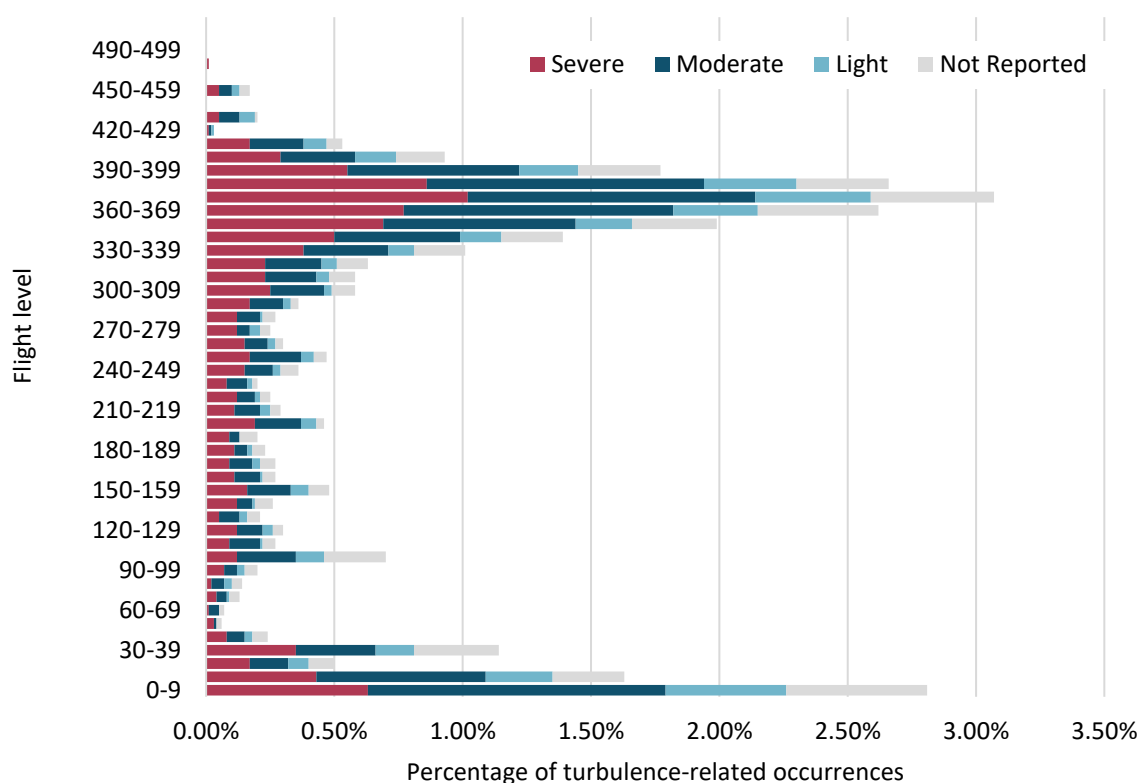


Figure 35 - Distribution of turbulence-related ECR occurrences by altitude (FL) and intensity level

5.3.3. Concentration of turbulent episodes at the end of cruise and the role of on-board weather radar technology

A particularly striking feature emerges when analysing the distribution of turbulence episodes in the recorded flight data by flight phase progress, defined as the percentage of time elapsed from the start of the flight phase in which the episode occurs until the time at which the episode takes place divided by the duration of the phase. Additional information regarding the definition of phase progress and how the figures presented in this section are constructed can be found in Appendix C.2.

Figure 36 shows the probability density function of turbulence episodes as a function of phase progress for all five flight phases. When examining the figure, it is crucial to note that the probability densities can only be compared within each flight phase, and not across flight phases. In the initial climb, climb, approach, and descent phases, the occurrence of turbulence episodes concentrates at the lower altitude segment within each phase, reflecting the low altitude skew of turbulence episodes in the recorded flight data. The distribution during the cruise phase rises to a pronounced peak close to its end, near the top of descent, highlighted by the dotted region in Figure 36. This peak at the end of the cruise flight is a remarkable finding that deserves further analysis.

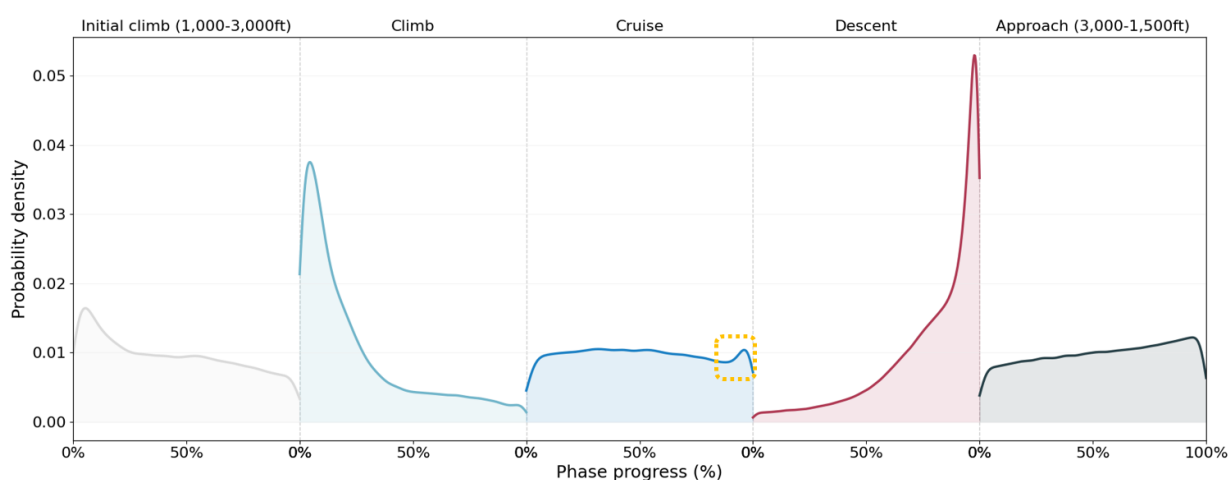


Figure 36 - Probability density of turbulence episodes with respect to phase progress, by flight phase⁷ (recorded flight data)

A possible explanation for the peak at the end of cruise is presented and analysed in detail in the following paragraphs. The first and most important factor to consider is the type and use of the on-board weather radar. The transition from cruise to descent may require management of the on-board weather radar to maintain an effective scan ahead, including adjustment of the antenna tilt as altitude and range change, and reconfiguration of other radar settings as appropriate. In particular, older-generation weather radars may require manual adjustment of both antenna tilt and gain, whereas more modern multiscan weather radars can perform much of this adjustment automatically and incorporate temperature-based gain management. If the weather radar is not managed properly, developing convective cells ahead may go undetected or their severity may be underestimated. On aircraft equipped with a manual weather radar these tasks must be performed by the crew, whereas more modern radar technology can perform much of the required adjustment automatically and can compensate for the reduced radar reflectivity associated

⁷ Each phase is normalised independently over its own 0% to 100% range; density values are comparable within a phase but not between phases.

with ice crystals at cold temperatures. This may improve the detection and depiction of convective activity, particularly at higher altitudes.

The second factor to consider is that the transition from cruise to descent is a demanding portion of the flight for the flight crew, raising crew workload as they perform the necessary SOPs. However, other human factors may also affect the effective use of manually managed weather radar, including pilot proficiency in manual tilt and gain adjustment, the level of attention allocated to radar management, and the adequacy of pilots' mental models of radar behaviour and limitations. These factors may influence radar management independently of workload and may therefore also contribute to differences in likelihood of turbulence detection between aircraft equipped with different radar technologies.

Combining these factors, the proposed hypothesis behind the peak at the end of cruise is that differences in weather radar technology may contribute to the observed increase in the number of turbulence encounters during this portion of the flight. Aircraft equipped with older generation weather radars generally require active crew management of antenna tilt and gain and may provide less effective detection or depiction of convective weather, whereas more modern multiscan radars can automatically manage these parameters and incorporate temperature-based gain adjustments.

If weather radar technology is a contributing factor to the observed peak at the end of cruise, aircraft with older generation technology, including weather radars that require active crew management, should exhibit a more pronounced peak than aircraft equipped with more modern onboard radars capable of automatic adjustment and advanced weather analysis. To test this hypothesis, the fleet available in the set of recorded flight data was divided into two groups: an older generation fleet (A319, A320, A321 and B737 NG) and a newer generation fleet (A320neo and B737 MAX), which differ in their typical weather radar capabilities. The newer aircraft types are typically equipped with weather radars featuring automatic tilt management and more advanced gain management/weather analysis, whereas the older aircraft types generally rely on manually managed weather radars with more limited detection capabilities.

Figure 35 shows the probability density function of turbulence episodes with respect to cruise progress for the two groups of aircraft fleet. During the final 10% of the cruise phase, marked by the dashed line in Figure 35, the peak is present in the older generation fleet but is absent in the newer generation fleet. The sample sizes for both groups are substantial, comprising approximately 54,000 and 22,000 cruise episodes respectively, making it unlikely that this difference is the result of limited data. This finding suggests that aircraft generation, used here as a proxy for weather radar technology, is a relevant factor and is consistent with the hypothesis that automatic weather radar management reduces the increase in turbulence encounters at the end of the cruise, observed in aircraft equipped with older generation radar systems.

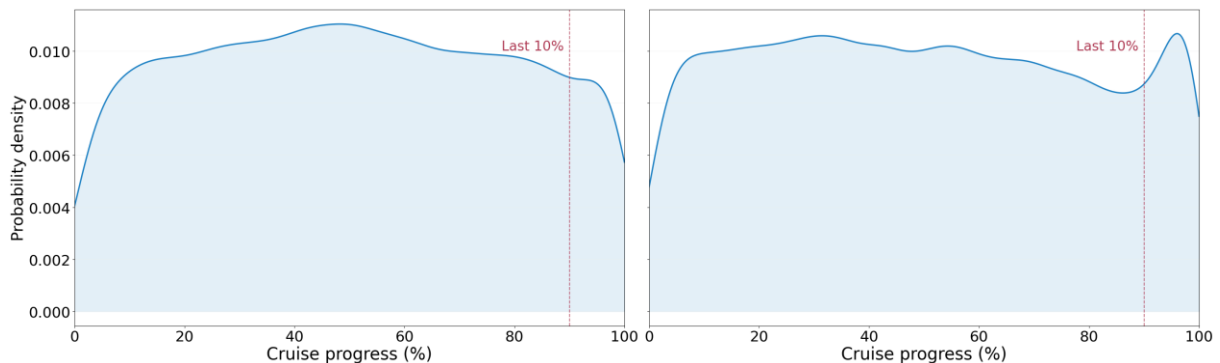


Figure 37 - Probability density of turbulence episodes with respect to cruise progress, by aircraft type (left = newer generation models, right = older generation models). Red dashed line marks last 10% of cruise phase

It must be noted that aircraft type is used as a proxy for the actual weather radar installation and its features, since different airframes, even within one aircraft generation, may have different weather radar configurations. Additionally, the effect of other differences between the aircraft generations cannot be excluded. Establishing the actual radar configuration at airframe level and repeating the comparison on that basis is a recommendation for future work. In addition, it is recommended to conduct a sensitivity analysis of the flight phase boundary rule that separates the end of cruise flight from the top of descent to assess whether the results are influenced by the definition of this boundary.

5.4. Injuries

Information on injuries is only available in the ECR data sample. Therefore, this section shows results based on the turbulence encounters from the ECR data set only (the recorded flight data does not contain information on injuries). Figure 38 shows the distribution of turbulence-related occurrences by injury severity level. Injuries are reported in approximately 15% of turbulence-related occurrences, split between 9% of occurrences that result in minor injuries versus 6.5% of occurrences that involve serious injuries. As discussed in Section 5.1.2 fatal injuries are extremely rare and based on further analysis were considered out of scope are therefore excluded from this analysis.

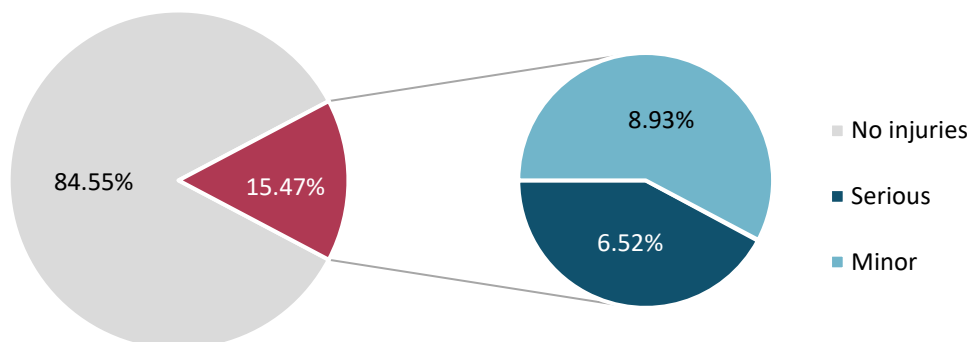


Figure 38 - Distribution of turbulence-related ECR occurrences by injury severity

The temporal evolution of the breakdown by injury severity, presented in Figure 39, shows a broadly stable injury-severity profile, although two periods require specific interpretation. First, the frequency of turbulence-related occurrences with injury declined during 2020 and 2021, with the sharpest reduction affecting serious injuries in 2020. This coincides with the COVID-19 pandemic, when reduced passenger loads and changes to cabin operations, including less frequent cabin service, likely reduced the number of people exposed to injury during turbulence encounters [21].

The second change occurs from 2023, when the overall rate of reported turbulence occurrences increases sharply, driven predominantly by occurrences without injury and, to a lesser extent, by occurrences with minor injuries. This supports the interpretation introduced in Section 5.2.1: the increase from 2023 onwards primarily reflects a shift in reporting practices resulting in increased reporting of lower severity events that may previously have gone unreported, rather than an increase in the likelihood of injury due to turbulence.

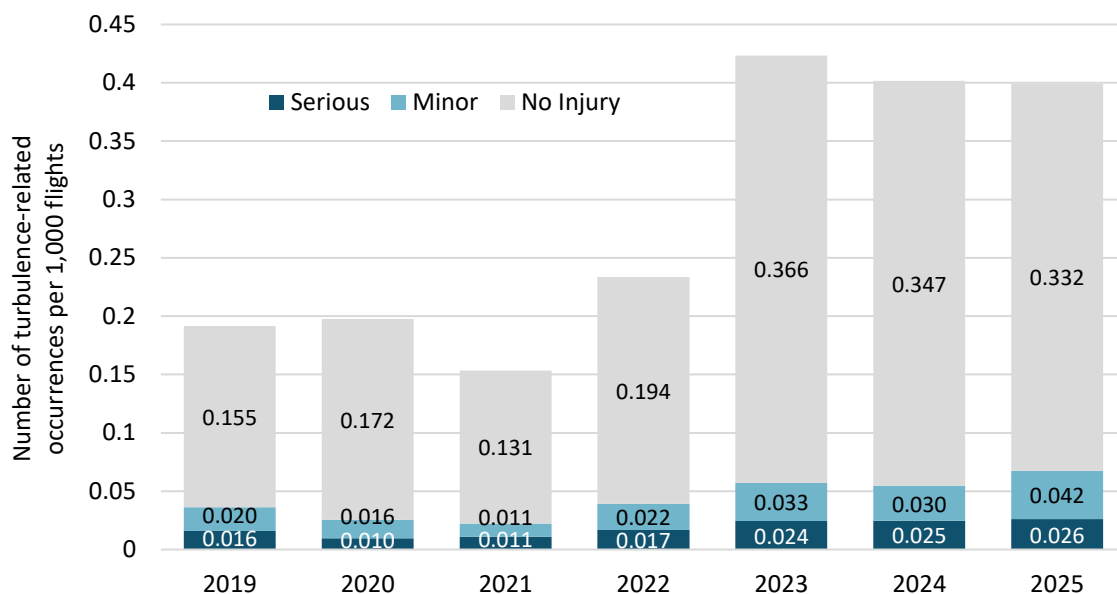


Figure 39 - Evolution of frequency of turbulence-related occurrences per 1,000 flights, by injury severity level

Figure 40 shows the distribution of turbulence-related occurrences with injuries by intensity level. Serious injuries are concentrated at moderate and severe intensities, with light turbulence producing very few injuries of any severity. The observed trend shows that at severe intensity, the percentage of events with serious injuries exceed events with minor injuries (17.53% against 15.95% of injured occurrences), whereas at moderate and light intensity occurrences resulting in minor injuries predominate. The severity of injury therefore increases with turbulence intensity, in both the likelihood of injury and the proportion of injuries that are serious.

This relationship should be understood in the context of the reporting bias in the ECR towards events with consequences, as explained in Section 5.1. The predominance of turbulence-related occurrences with injuries at moderate and severe intensity is partly a genuine physical effect, since a stronger aircraft response to turbulence is more likely to result in injury, and partly a reflection of the fact that occurrences with injury are reported because of mandatory occurrence reporting regulations.

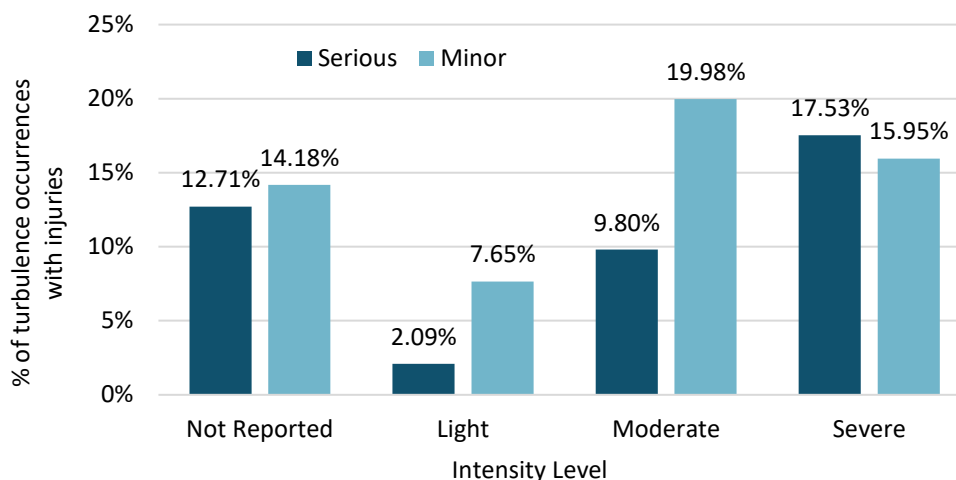


Figure 40 - Distribution of turbulence-related occurrences with injuries by intensity level and injury severity level

Figure 41 shows the distribution of injuries by injury severity level across flight phases. The share of occurrences involving injury is not uniform across phases. Cruise and descent show a higher rate of injuries at approximately 17% and 25%, respectively, while the remaining phases (initial climb, climb, and approach) range from 8% to 12%, approximately.

The increased proportion of injuries in cruise flight is attributed to two factors, both of which have already been introduced in the discussion regarding altitude and flight phase in Section 5.3. Firstly, clear-air turbulence, which has less predictability and is therefore more likely to be encountered unexpectedly than convective turbulence (as explained in Section 5.6), is most prominent in cruise. And secondly, cruise is characterised by increased cabin activity: passengers are more likely to be unrestrained and moving through the cabin (walking or using the lavatories), as well as activities performed by cabin crew such as performing cabin service taking place during cruise. The role of the activity during injury is explored in more detail below.

The increased proportion of injuries in descent also deserves attention. Descent shows a notably higher proportion of injuries than approach: approximately 24% of turbulence occurrences during descent involve an injury, against approximately 8% during approach, despite approach accounting for more occurrences overall, as shown in Section 5.3. This is attributed to the fact that some occupants may not be wearing their seatbelts during descent. During the initial climb and climb phases passengers are likely to be wearing their seatbelts since they are restrained prior to take-off and operator procedures may require the seatbelt sign to remain on until 10,000 ft, even in smooth conditions. Above this altitude, the sign may be switched off if no significant turbulence is present or expected; otherwise, it remains on until conditions permit. During approach passengers are also likely to be restrained in preparation for landing and this is checked by the cabin crew in a cabin safety check (similarly prior to take-off). The early stages of the descent phase, however, may coincide with ongoing cabin activities, passenger movement, or an incomplete transition to

a fully secured cabin, increasing the likelihood of injury compared to the approach phase, when the cabin is typically prepared for landing and seatbelt compliance is highest. The disparity between descent and the other non-cruise phases in the figures is therefore attributed to use of seatbelts, and not to the turbulence intensity level itself.

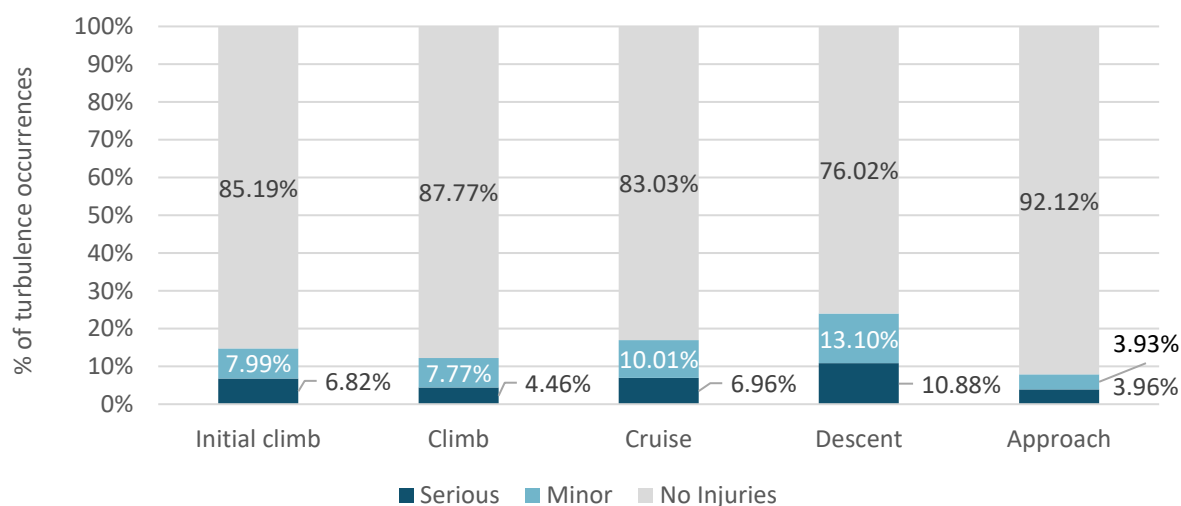


Figure 41 - Distribution of turbulence-related ECR occurrences by flight phase and injury severity level

Figure 42 shows the distribution of injuries in turbulence-related ECR occurrences by the affected personnel (passengers, flight crew, or cabin crew), and Figure 43 shows the breakdown of injuries within each type of personnel by injury severity level. Cabin crew account for the majority of injuries, followed by passengers, while the percentage of injuries involving pilots is an order of magnitude lower. The explanation for this observation is once again related to restraint and movement: while pilots remain seated with seat belts fastened for most of the flight, cabin crew members move through the cabin or galleys performing cabin service or other tasks, while passengers may walk around of visit toilets, particularly during cruise. Cabin crew members also have the highest proportion of serious injuries, while pilots have the lowest. Thus, the data shows that persons that are more frequently unrestrained experience higher likelihood of injury and a higher likelihood of a serious injury as well.

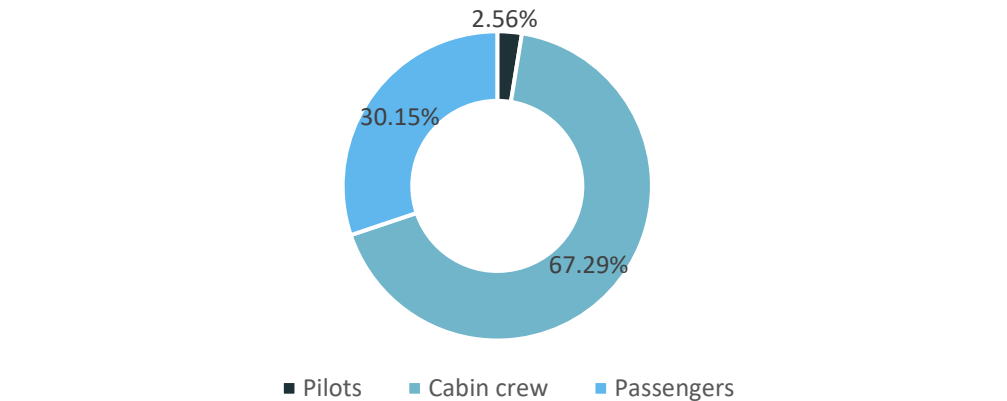


Figure 42 - Distribution of injuries in turbulence-related ECR occurrences by affected type of person

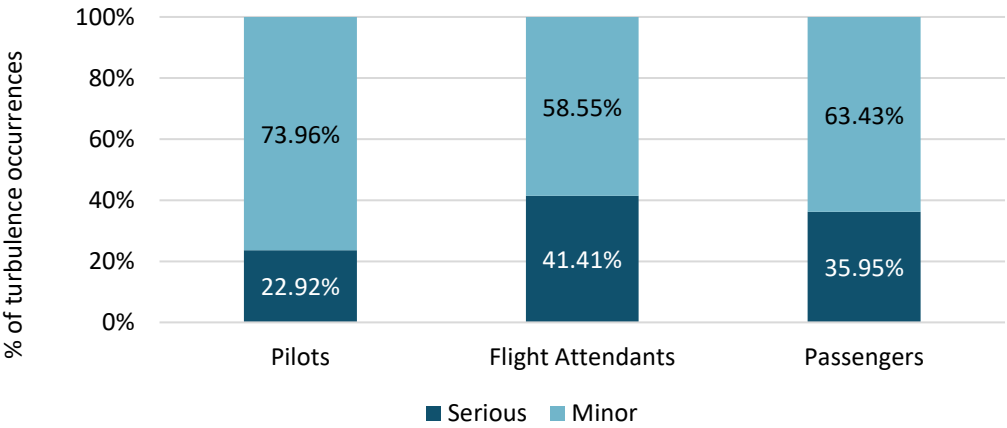


Figure 43 - Distribution of turbulence-related ECR occurrences by injury severity level and affected type of person (only known information⁸)

Figure 44 shows the breakdown of turbulence-related ECR occurrences with injuries by the activity taking place at the time the injuries occurred. The activities associated with the highest percentage of injuries share a common feature: the lack of restraint. These activities include performing cabin service, standing or walking in the cabin, and sitting without a fastened seatbelt. This finding shows the relationship between use of seatbelts and injury previously established.

⁸ Scope includes turbulence-related occurrences with injuries with known injury severity level and where the affected type of person is also known.

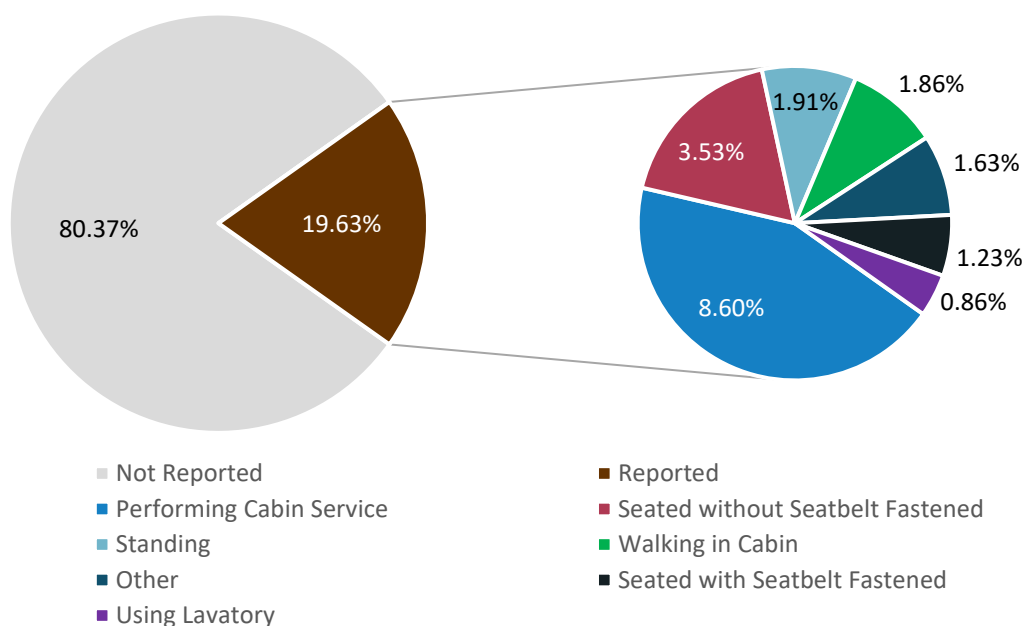


Figure 44 - Distribution of turbulence-related ECR occurrences with injury by activity during injury

Figure 45 and Figure 46 show the breakdown by activity for occurrences with injuries to cabin crew and passengers, respectively. It should be noted that the methodology used to process the ECR data, described in Section 4.1, has an important limitation in relation to the activity field. The methodology does not associate each individual injury to a specific type of person and activity. Instead, it records all of the injuries, activities during injury, and affected personnel within each occurrence at an aggregate level. In other words, the information is recorded at the occurrence level and not at the level of individual injuries.

This drawback has two implications. First, in occurrences with multiple injuries there may be a single activity associated with the injuries or multiple activities, depending on the data included in the occurrence report. A one-to-one match of each individual injury to an individual activity is not possible. Instead, each occurrence gets a classification of the activities being performed at the time of turbulence. Secondly, this limitation implies that there may be overlap between the data of Figure 45 and Figure 46. Occurrences where both passengers and cabin crew were injured will appear in both figures, and they may be associated with one or multiple activities.

Consider, as an example, the activity “Performing Cabin Service”. Cabin service is an activity performed by cabin crew, and yet it also appears as an activity associated with occurrences with passenger injuries (Figure 46). This could mean two things: either that passengers were injured in relation to the cabin service (for example due to a collision with a trolley), or that passengers were injured for unrelated reasons (another activity) in the same occurrence during which cabin crew (or other passengers) were injured while cabin service was in progress (e.g. cabin crew injured while performing cabin service and passengers injured while using the lavatory in the same occurrence). Resolving this ambiguity is not possible with the available data.

Consequently, the data in Figure 45 and Figure 46 should only be interpreted in general terms, observing the relative changes in the distribution of activity between occurrences with flight attendant injuries versus those with passenger injuries.

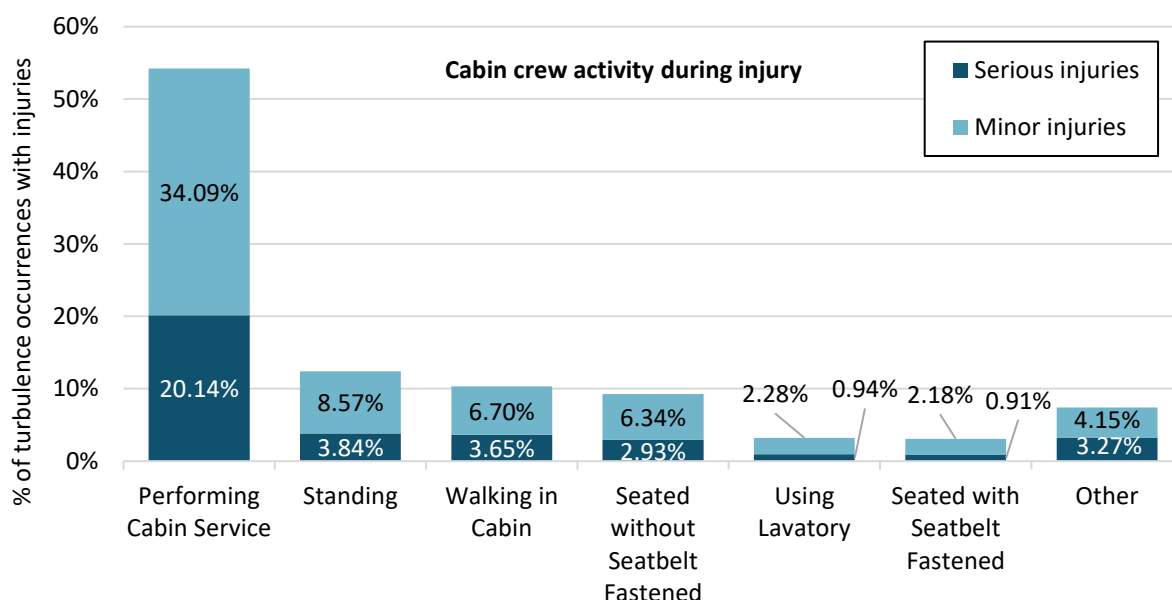


Figure 45 - Distribution of injuries amongst cabin crew by activity during injury and injury severity level

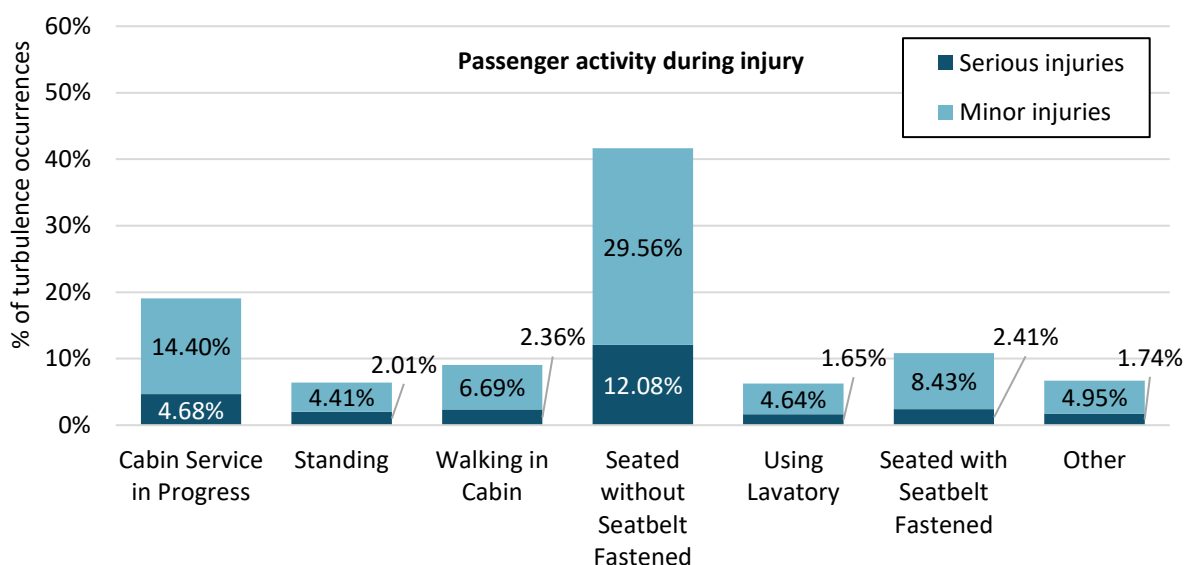


Figure 46 - Distribution of injuries amongst passengers by activity and injury severity level⁹

The data of Figure 45 and Figure 46 show that the two groups have a distinctive activity-related injury profile. For cabin crew, cabin service is the dominant activity during which injury occurs in a turbulence

⁹ Note that the category “Cabin Service in Progress” refers to the same attribute as “Performing Cabin Service” in Figure 45. The category has been renamed to better reflect the passenger activity.

encounter, while for passengers the activity associated with injury likelihood is “seated without a seatbelt fastened”.

For cabin crew, performing cabin service presents the most frequent observed activity related to injury, followed by standing and walking in the cabin. These activities require cabin crew members to walk around or standing in the cabin unrestrained, increasing their vulnerability during a turbulence encounter. Although the resulting injuries are more frequently minor than serious, serious injuries occur across all activity categories. This reinforces the importance of timely detection of turbulence and timely preparation of the cabin, e.g. communication to the cabin crew by pilots, suspension of cabin service and taking seats/fasten seatbelts whenever conditions permit.

Passengers are at least three times more likely to be injured when seated without a fastened seatbelt than when wearing one, and injuries sustained by unrestrained passengers are also more likely to be serious. The analysis shows that aircraft occupants who were seated with their seat belt fastened at the time of a turbulence encounter have a lower likelihood of injury and are also less seriously injured, which shows the benefit and importance of seatbelt use among seated passengers.

Figure 47 shows the distribution of turbulence-related occurrences by injury location. The aforementioned limitation regarding the inability to identify the activity during injury for each individual or injury also applies to the location within the cabin where the injury took place. As with activity, injury location is not reported in the large majority of occurrences, accounting for approximately 81% of the dataset. This limits the extent to which conclusions can be generalised. For the analysis, the passenger-seating area and aisle were combined into a single “passenger cabin area” category. This is the most frequently identified injury location, accounting for approximately 8.5% of injury-related occurrences, followed by the galley at approximately 6.5%.

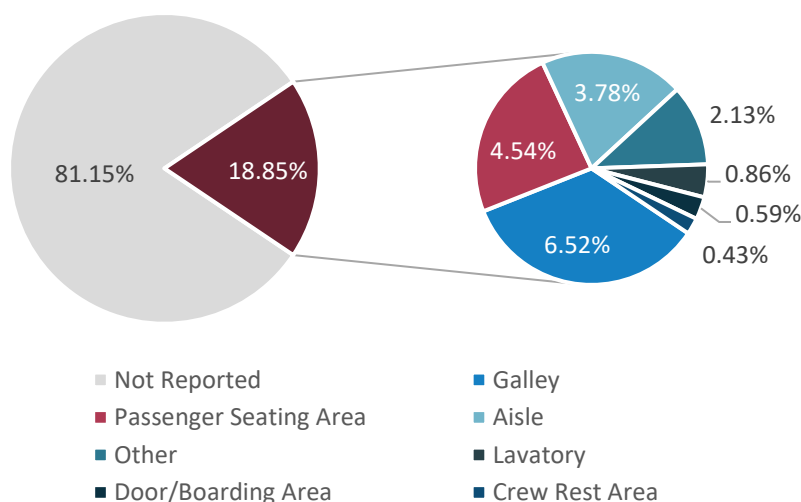


Figure 47 - Distribution of turbulence-related occurrences by injury location

Figure 48 shows the temporal evolution of the distribution of occurrences with injury by cabin location, with the “Not Reported” category excluded. The passenger cabin area and galley are the most frequently reported injury locations throughout the study period, although their relative shares fluctuate between years. A modest reduction in the galley share and an increase in the crew rest area share are visible in 2020, but these changes are neither sufficiently pronounced nor persistent to indicate a clear pandemic-related effect. Overall, the figure shows normal year-to-year variation rather than a sustained temporal trend.

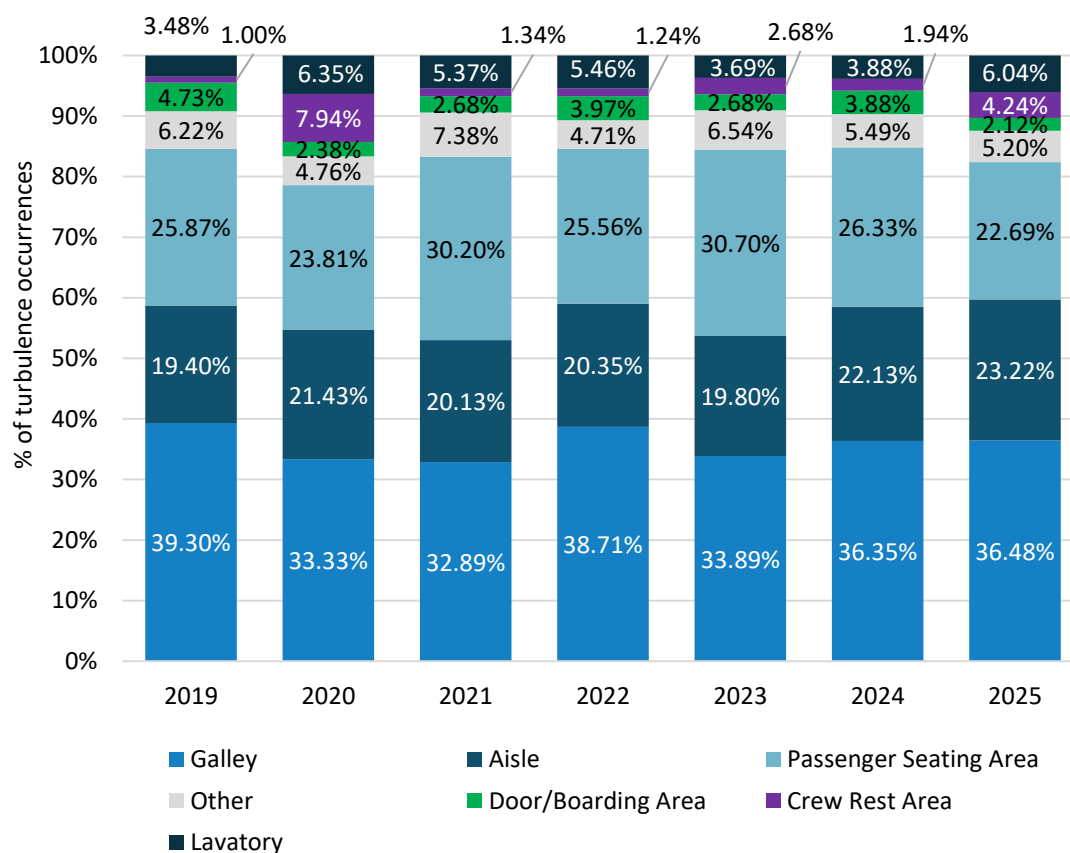


Figure 48 - Evolution of the distribution of injuries in turbulence-related ECR occurrences by injury location, when injury location is known (“Not reported” location is excluded)

Figure 49 and Figure 50 show the breakdown by injury location for occurrences with cabin crew and with passenger injuries, respectively. The two figures are consistent with the findings for activity during injury. Flight-attendant injuries are associated principally with the galley and the combined passenger cabin area, reflecting their movement between the galley, aisle and passenger-seating area while performing cabin duties. The location data therefore refine the activity picture: the cabin service injuries sustained by cabin crew appear to occur most frequently in the galley rather than in the aisle. Passenger injuries are most often associated with the passenger seating area since that is the location where passengers spend most of their time during flight.

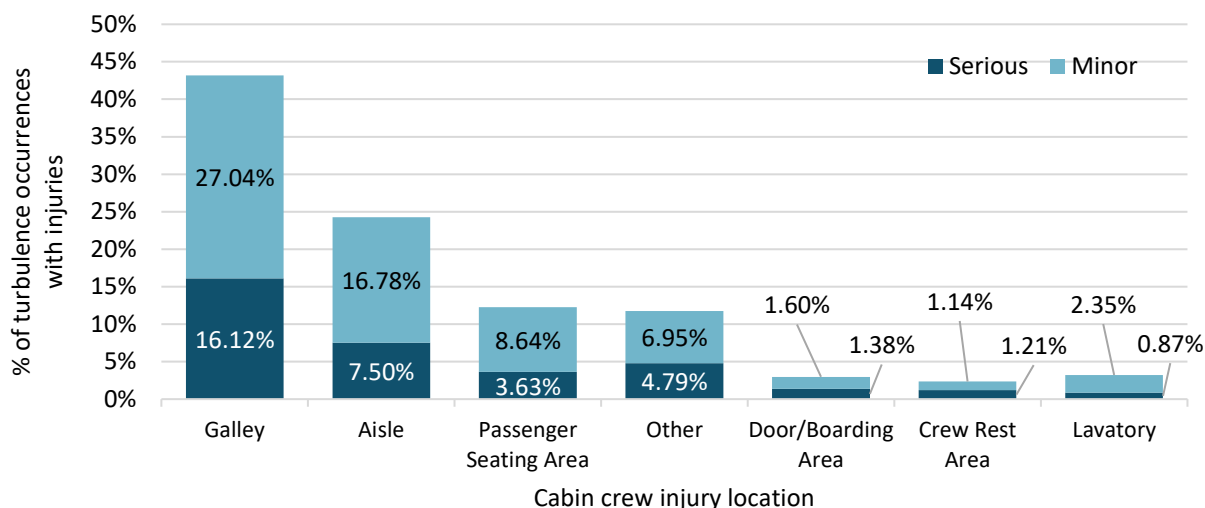


Figure 49 - Distribution of injuries affecting cabin crew in turbulence-related occurrences by injury location and injury severity level

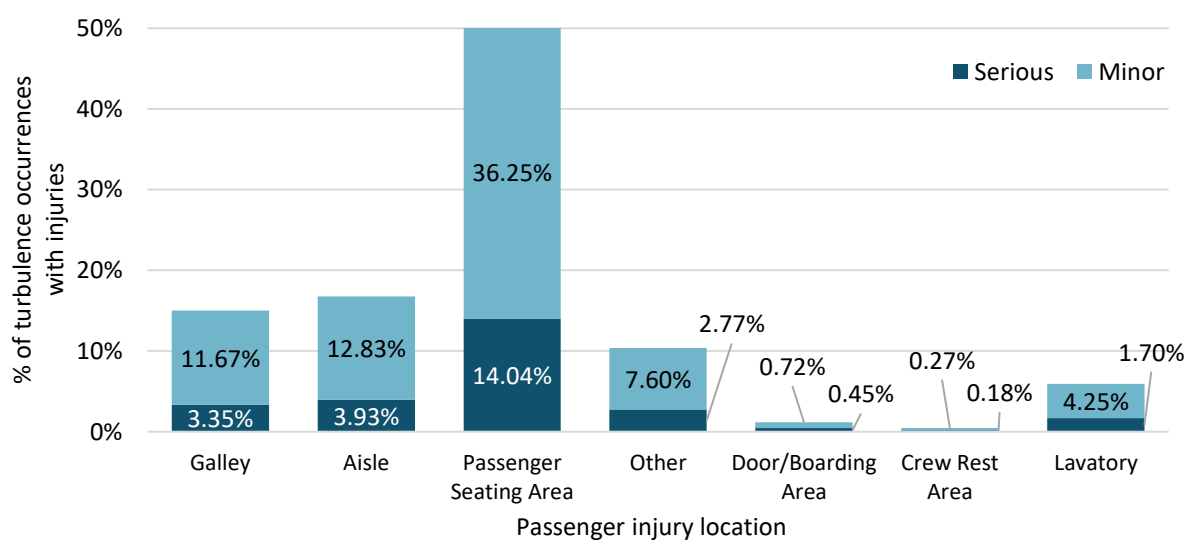


Figure 50 - Distribution of injuries affecting passengers in turbulence-related occurrences by injury location and injury severity level

5.5. Aircraft damage

Similarly to the analysis of injuries in the previous section, information on aircraft damage is only available in the ECR data sample, so this section shows results based on the turbulence encounters from the ECR data set only (the recorded flight data does not contain information on aircraft damage).

Figure 51 shows the distribution of turbulence-related occurrences in the ECR data sample by severity level of aircraft damage. The damage severity level of an occurrence is the highest damage severity recorded

within that occurrence. Where an occurrence records both minor and substantial damage, for example, it is assigned the higher of the two.

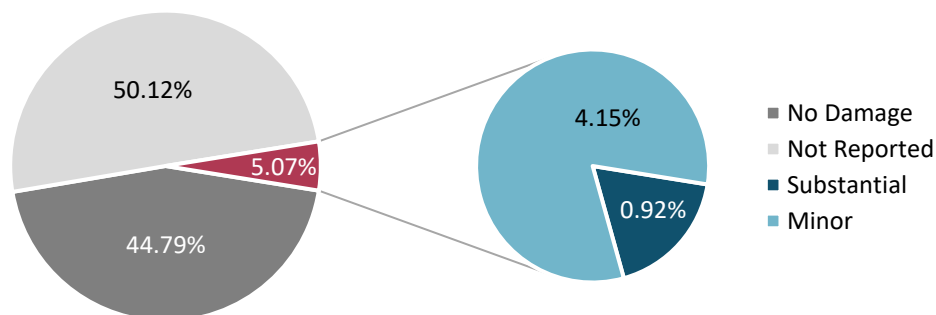


Figure 51 - Distribution of turbulence-related ECR occurrences by damage severity level

Turbulence rarely causes damage to the aircraft. Approximately half of the occurrences have a reported damage severity level; 45% of the total occurrences reported that no damage occurred (severity level No Damage) and only 5% of the total occurrences reported damage (4% minor and 1% substantial). It is worth noting that injuries, discussed in Section 5.4, are reported about three times as frequently as aircraft damage in the turbulence-related ECR occurrences (approximately 15% of occurrences report injuries versus the 5% reporting damage shown here).

The aircraft damage severity levels represent qualitative descriptions available in taxonomy fields; we have no information on actual loads or evidence of structural damage or failures as result of turbulence other than what was reported by the reporter:

- **Minor damage** can be corrected through simple repair or component replacement without an extensive inspection.
- **Substantial damage** adversely affects structural strength, performance or flight characteristics and normally requires major repair or replacement.
- **Destroyed** (not present in Figure 51) indicates that the principal structural elements or systems are damaged so extensively that restoring the aircraft to an airworthy condition would be impractical; it is a technical classification and is not determined solely by whether repair is economically viable.

The highest damage category (“Destroyed”) occurs only among the very high severity outliers discussed in Section 5.1.2. The combined ECR and recorded flight data evidence indicates that the likelihood of turbulence alone causing primary airframe or structural damage is essentially null. This is consistent with severe turbulence and operational load exceedances being extremely rare in the recorded flight data (see Sections 5.2 and 6.2.1.5), and with transport-category aircraft being certified to withstand prescribed manoeuvre and gust loads with safety margins. Minor damage to replaceable or non-primary components may still occur without implying any loss of primary structural integrity.

It should be noted that the ECCAIRS2 taxonomy used in the ECR dataset has an attribute that could, in principle, be useful to identify the specific parts that suffered damage in those occurrences where damage is present (the “Parts Damage” attribute). However, in the ECR dataset used in the present study, this field is reported in less than 1% of occurrences. It is therefore not possible to determine systematically whether the reported damage affected the primary structure, secondary structure, systems, interiors or easily replaceable components.

Consider now the relationship between damage severity level and intensity level, shown in Figure 52. Damage severity increases with turbulence intensity: both the minor and substantial damage shares rise from light through moderate to severe. Among those occurrences where damage is sustained, the damage severity level is predominantly minor across all intensity levels.

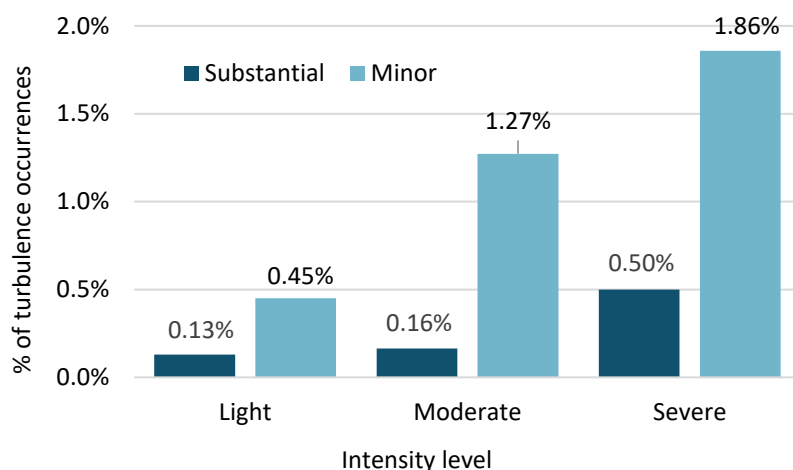


Figure 52 - Distribution of occurrences with minor and substantial damage severity level by intensity level

The association between higher intensity and greater damage should be interpreted with care. Moderate and severe occurrences are considerably more prevalent in the ECR data set than light intensity occurrences. This over-representation reflects the reporting bias towards events with consequences discussed in Section 5.1. This bias may contribute to the observed relationship between intensity and damage, which should therefore not be read as a direct measure of the physical propensity of each intensity level to cause damage. The relationship between turbulence and aircraft damage is examined further in the analysis of consequential events (Chapter 6).

Finally, Figure 53 shows the temporal evolution of the frequency of turbulence-related ECR occurrences of all damage severity levels (including “No Damage” and “Not reported”) normalised per 1,000 flights. The share of occurrences involving damage remains broadly constant until 2023, at which point the “Not Reported” damage category increases sharply. This aligns with the shift in reporting practices identified in 5.2.1: the increase is concentrated in occurrences where damage is not reported, consistent with a greater

number of lower severity turbulence-related events entering the ECR data set from 2023. The pattern is reinforced over the following years, as the proportion of “Not Reported” damage decreases from 2023 to 2025 while the proportion of occurrences reported with no damage increases, indicating a progressive improvement in the completeness of the damage taxonomy field rather than a change in the underlying rate of damaging events.

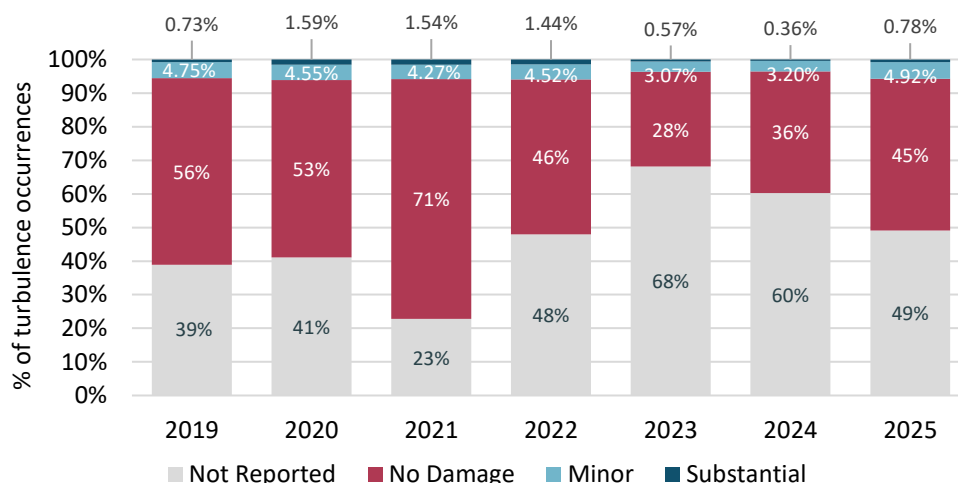


Figure 53 - Evolution of the distribution of turbulence-related occurrences by known damage severity level (all occurrences included)

5.6. Turbulence type

Similarly to the analysis of injuries (Section 5.4) and aircraft damage (Section 5.5), the analysis of turbulence type presented in this section can only be performed using the ECR dataset, where the turbulence type attribute is obtained through the processing of the available narrative and free-text fields in each occurrence using the LLM enhancement process described in detail in Section 4.1.4. The recorded flight data sample does not contain any meteorological data and cannot be used to infer the type of turbulence.

Figure 54 represents the breakdown of turbulence-related ECR occurrences by turbulence type. It should be noted that the breakdown shown here refers to the sample of ECR occurrences used in the present study, where only specific turbulence types are considered according to the definition of the scope presented in Section 3.2 (see Section 3.2.4 in particular). Therefore, the data shown here may not be representative of the entire ECR dataset; the data is constrained by the scope of the study to occurrences where the turbulence type is either “Not reported” or reported and equal to one of the values within the scope of the study (namely convective turbulence or clear-air turbulence).

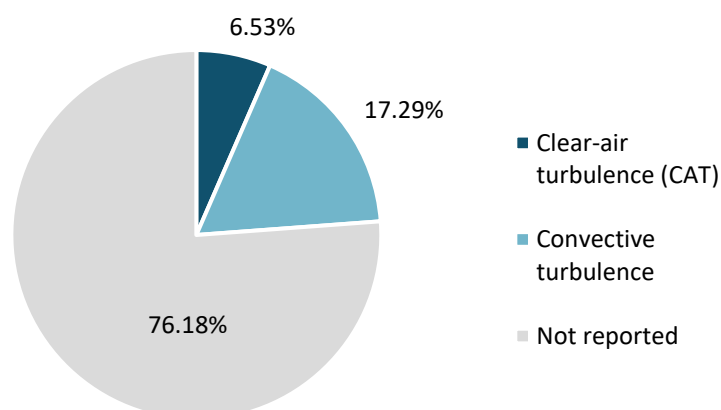


Figure 54 - Breakdown of turbulence-related ECR occurrences by turbulence type

Figure 54 shows that turbulence type is not reported in approximately three quarters of the available ECR occurrences. For those occurrences with a turbulence type classification present, the figure shows that convective turbulence is about two and a half times more frequent than clear-air turbulence in the data sample.

The role of the “Not Reported” category in this analysis deserves particular attention. In previous sections, the treatment of occurrences where the analysed attribute belongs to the “Not Reported” category was more straightforward. For example, in the analysis of injuries presented in Section 5.4, it stands to reason that if an occurrence records the injury severity level as “Not Reported”, there were no significant injuries present, as otherwise their severity level would have played a significant role in the occurrence report and would therefore be available as a reported attribute. That is not necessarily the case here in the analysis of turbulence type. When it comes to turbulence type, the fact that the attribute is “Not Reported” cannot be used to infer any conclusions about the actual turbulence type of the underlying turbulence encounter. For that reason, the analysis presented in the remainder of this section should be taken with caution, understanding that the conclusions regarding turbulence type presented in the following paragraphs are only representative of the subset of data where the turbulence type is reported (approximately 25% of the occurrences in the ECR sample used in the present study).

Figure 55 shows the temporal evolution of the distribution of turbulence occurrences with a reported or known turbulence type, showing that the relative proportion of the two turbulence types is approximately constant throughout the study period (2019-2025).

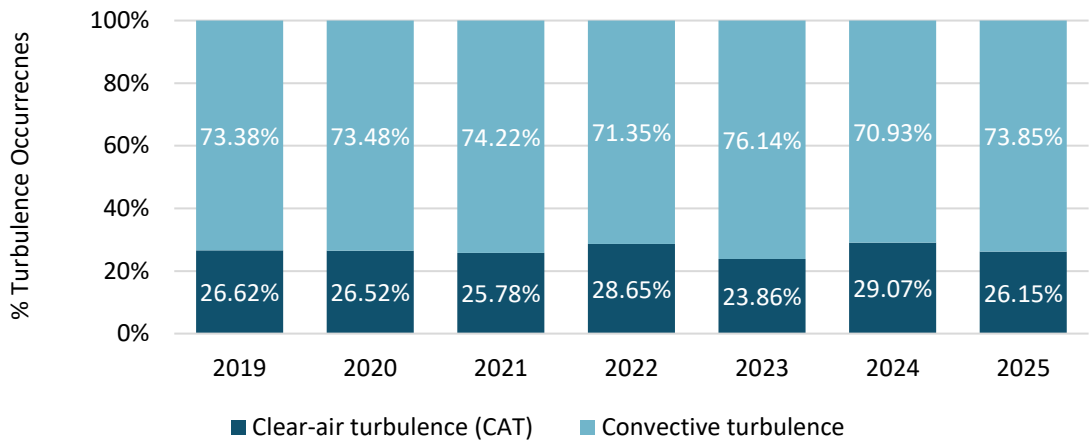


Figure 55 - Evolution of the distribution of turbulence-related occurrences with known turbulence type by turbulence type

Figure 56 shows the percentage of occurrences with and without injury per turbulence type. Note that the “Without injury” category includes occurrences where “No injury” was reported and occurrences where the injuries field was left unreported. The figure shows that clear-air turbulence is significantly more likely to cause injuries than convective turbulence. Approximately 20% of CAT occurrences result in injuries, compared with under 10% of convective turbulence occurrences, and approximately 16% for occurrences of unreported turbulence type. The average of the entire dataset, as discussed in Section 5.4, is approximately 15%. It can therefore be stated that, in terms of proportion of occurrences with injuries, those associated with CAT are clearly above the mean at 20%, while those associated with convective turbulence are below average at under 10%.

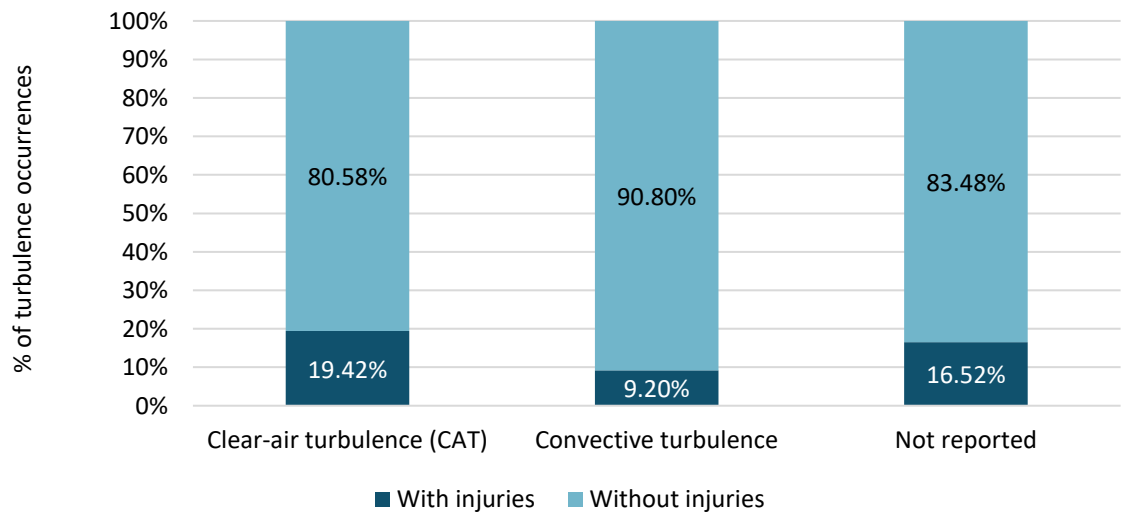


Figure 56 - Percentage of turbulence-related ECR occurrences with and without injuries by turbulence type

Figure 57 shows the injury severity level by turbulence type and there appears to be no difference regarding injury levels between the two types of turbulence. Turbulence type therefore appears to be associated with the likelihood of injuries, but not the severity of those injuries when they occur. The higher likelihood of injury associated with CAT may be partially explained by its lower predictability. Convective weather activity can be detected through the on-board weather radar and weather reports, allowing the flight crew to more easily anticipate convective turbulence and take the necessary measures, such as stopping cabin service, secure the cabin in preparation for turbulence, etc. By contrast, clear-air turbulence (CAT) cannot be detected by conventional weather radar and may be anticipated through Significant Weather (SigWx) charts and pilot reports (PIREPs) from aircraft in the vicinity. In addition, modern connected Electronic Flight Bags (EFBs) may display near-real-time or recorded turbulence data shared by other aircraft through programs such as IATA Turbulence Aware. However, the availability and coverage of such reports depend on the participating aircraft and the extent of network coverage [13]. As a result, CAT encounters are more likely to occur with little to no warning compared to encounters with convective turbulence, leaving less or no time for the crew to prepare and secure the cabin for turbulence.

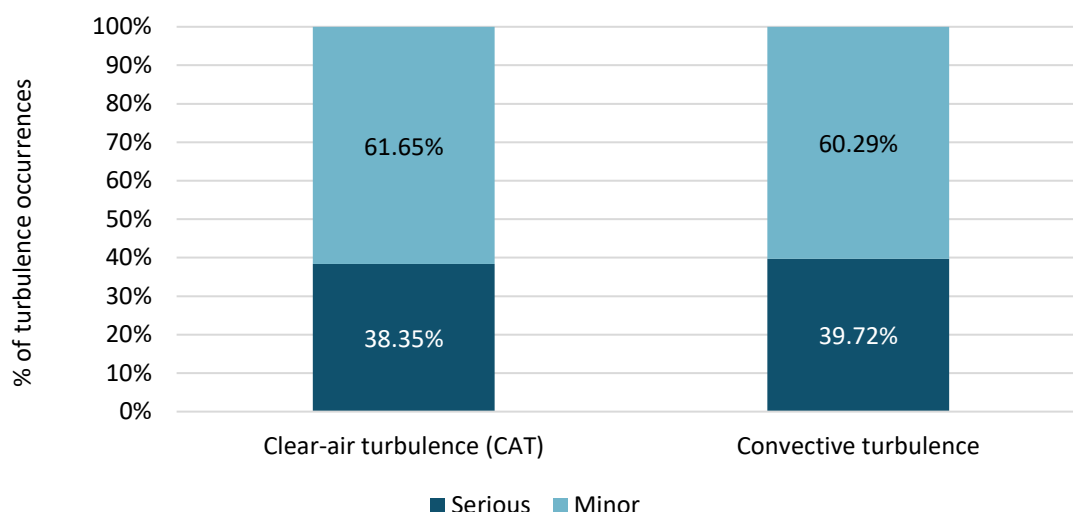


Figure 57 - Distribution of turbulence-related ECR occurrences with injuries of known severity level and known turbulence type¹⁰

Consider now the distribution of occurrences by turbulence type and altitude, shown in Figure 58: the two types of turbulence differ in the altitudes at which they occur. The data sample shows that CAT occurrences occur almost entirely at cruise flight levels, whereas convective turbulence occurrences appear across a broader range of altitudes and notably in the lower altitude bands. The “Not Reported” category is evenly spread across altitude bands. It must be noted that this is the distribution of occurrences by turbulence type *in the ECR dataset*, that is, those that had consequences that required reporting to the ECR. The data

¹⁰ Note: Only occurrences with known injury severity and turbulence type are included.

shown may not be representative for the actual altitude distribution of convective and clear-air turbulence in the atmosphere.

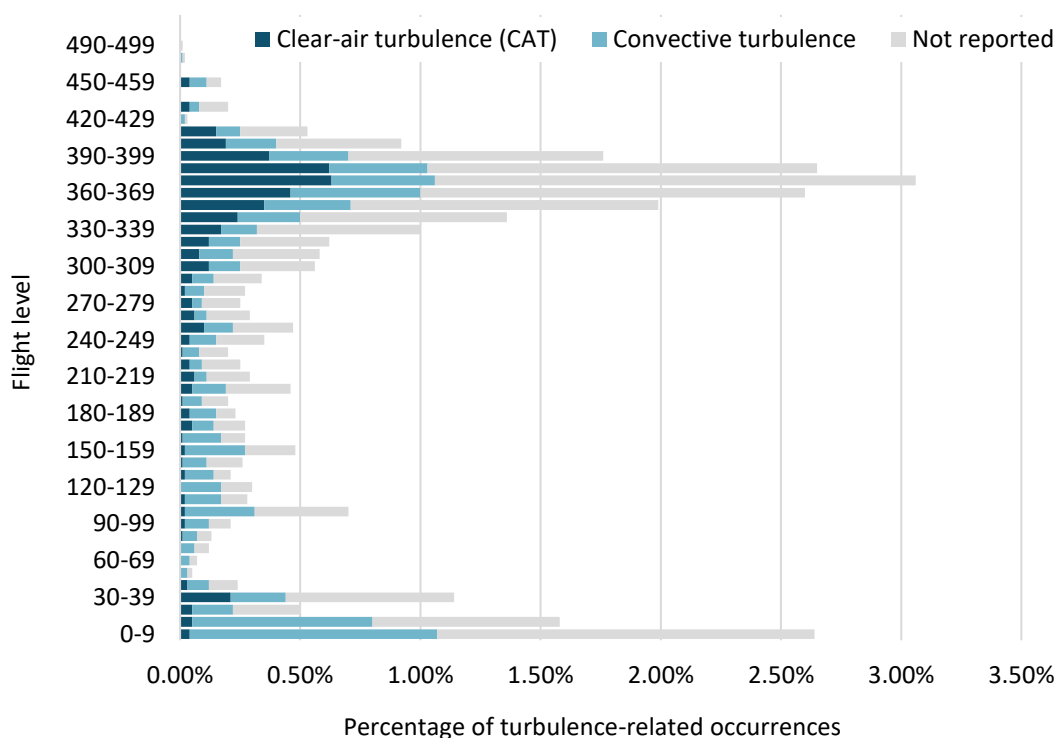


Figure 58 - Distribution of turbulence-related ECR occurrences by altitude (flight level) and turbulence type

The same trend is visible in the breakdown of occurrences by turbulence type and flight phase, shown in Figure 59. CAT occurs almost entirely during cruise. Convective turbulence is also most present during cruise but is of similar relevance during approach, and to a lesser extent during climb and descent. This aligns with the results of the altitude distribution, where CAT was confined to cruising altitudes and convective turbulence appeared across a broader range of altitudes.

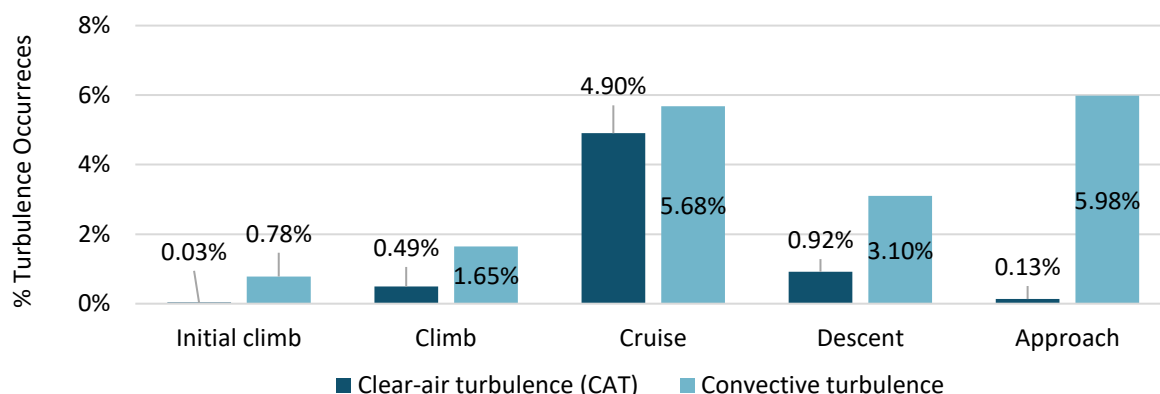


Figure 59 - Distribution of turbulence-related occurrences by flight phase and turbulence type

Consider now the distribution of the two turbulence types by intensity level. Figure 60 shows that CAT is concentrated in the moderate and severe categories, whereas convective turbulence has a greater share of lower intensity occurrences. This is consistent with greater proportion of injuries in CAT occurrences versus those with convective turbulence discussed above.

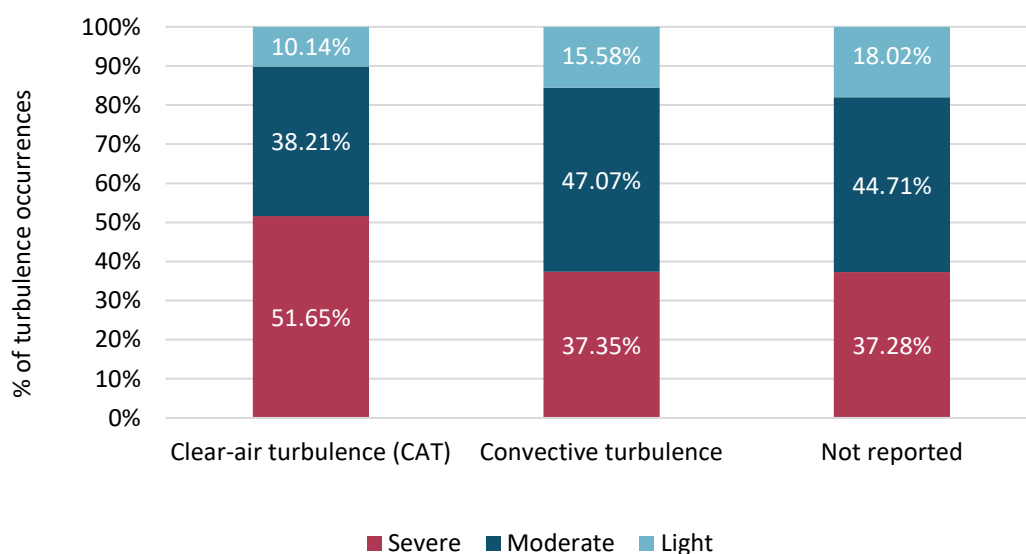


Figure 60 - Distribution of turbulence-related ECR occurrences by turbulence type and intensity level

In summary, the findings presented in this section show that in the turbulence-related ECR occurrences for which the type of turbulence is known, several trends can be observed. Firstly, CAT is associated with higher severity occurrences. Secondly, CAT has an increased likelihood of injuries compared to convective turbulence, but the severity of the injuries is equivalent across the two turbulence types. And thirdly, that CAT is mostly present at cruising altitudes whereas convective turbulence occurrences are more evenly spread out across a broader altitude range (and therefore more evenly spread across flight phases).

These findings should be read together with those of the preceding sections, in particular the breakdown by altitude and flight phase in Section 5.3 and the analysis of injuries in Section 5.4. They do not imply that clear-air turbulence is inherently more intense than convective turbulence (in terms of the magnitude of the aircraft's response to turbulence), nor that its consequences are inherently more severe. The higher injury likelihood associated with CAT arises instead from where and how it is encountered. As previously discussed, CAT cannot be detected by on-board weather radar, so it is more often unanticipated and leaves less time to secure the cabin; and it occurs predominantly in cruise, the phase of greatest cabin activity, when passengers and cabin crew are most likely to be moving about unrestrained, which Section 5.4 identified as the leading source of passenger injuries. The combination of an unforeseen encounter and an exposed cabin is what produces the greater proportion of injury-bearing occurrences (and hence the higher severity) associated with CAT as presented in this section.

This finding is consistent with results in Section 5.3. Although the cruise phase has the lowest frequency of turbulence per unit of flight time, it is disproportionately represented in the ECR data set, accounting for the largest number of turbulence-related occurrences. The reasons explained previously are reinforced here. The presence of CAT poses a challenge as its difficulty to be detected reduces the time available for cabin preparation, and together with the cabin activity and passenger movements during cruise explains the contrast between the results from the recorded flight data versus the turbulence-related occurrences in the ECR.

Finally, these findings have an important implication in the context of climate change. A warming climate is expected to increase both clear-air and convective turbulence, but the physical and observational evidence linking climate change to clear-air turbulence (CAT) is substantially more consistent. CAT is associated with vertical wind shear in the vicinity of upper-level jet streams, and anthropogenic warming is expected to strengthen the temperature gradients and associated wind shear at aircraft cruising altitudes [22]. This is supported not only by climate-model projections but also by observations: wind shear in the jet stream has increased since satellite observations began in the 1970s [23], while an increase in severe CAT has been observed over the North Atlantic since 1979 [24]. Future projections indicate that severe CAT could become approximately two to three times more frequent over the period 2050–2080 [25].

Convective turbulence is also expected to intensify in a warmer climate, as higher atmospheric moisture and convective available potential energy can favour more vigorous convection and severe thunderstorms. However, projections of future changes in convective turbulence remain considerably more uncertain, with substantial regional variation and, in some regions, disagreement even on the direction of the projected trend [26] [27].

The relevance to the present study is direct. CAT is the turbulence type identified here as being associated with the highest likelihood of injury. A future increase in CAT exposure would therefore act on a turbulence type for which the study has already identified a particular vulnerability. Improving the detection and

forecasting of CAT and providing earlier and more reliable turbulence information to flight crews should consequently remain a priority. For convective turbulence, continued improvement in onboard weather-radar capability remains important for early detection, avoidance and mitigation. The climate-change projections do not alter the findings of this study, but they increase their forward-looking significance and reinforce the need to monitor how the turbulence exposure and associated consequences identified here evolve over time.

5.7. Route type

Consider now the distribution of turbulence encounters across routes of different types. Several different classifications of routes could be considered, but the analysis is partially restricted by Data Governance constraints. This has two important implications. Firstly, the analysis by route type is restricted to the ECR dataset only. Secondly, the analysis by route type is limited to the distinction between short-haul and long-haul routes (flights).

The turbulence-related occurrences from the ECR dataset have been classified as belonging to a short-haul or long-haul flight using a distance threshold of 4,000 km, following the definition typically used by European regulators and stakeholders such as EASA [28] and Eurocontrol [29]. For each occurrence, the distance between the reported origin and destination points is computed¹¹, and the occurrence is then classified as belonging to a short or long-haul flight accordingly.

Short-haul flights account for approximately two thirds of the turbulence-related ECR occurrences, while long-haul flights make up approximately 30%, as shown in Figure 61. Around 5% of occurrences have an unreported route type, due to either the origin or destination being unreported. It should be noted that this distribution cannot be normalised on a per flight basis through the exposure dataset, since the exposure dataset lacks differentiation between short and long-haul flights. As a consequence, it cannot be concluded from the data the extent to which the distribution shown in Figure 61 is simply a reflection of the underlying distribution of short and long-haul traffic over the geographical areas covered by the ECR.

¹¹ The great circle distance (GCD) between the coordinates of the origin and destination airport is used.

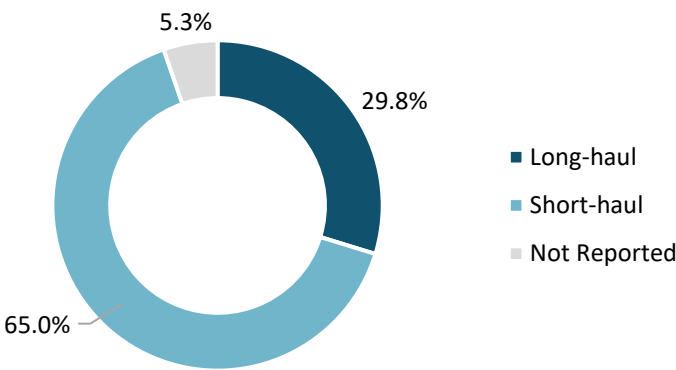


Figure 61 - Distribution of turbulence-related ECR occurrences by route type

Figure 62 and Figure 63 compare the turbulence characteristics of the two route types in terms of turbulence type and intensity level, respectively. Long-haul flights show a higher proportion of clear-air turbulence occurrences and a higher proportion of severe occurrences compared to short-haul flights. The difference appears to reflect the distribution of flight phases across the two route types rather than route type itself. Long-haul flights spend a larger proportion of their flying time in cruise, where CAT is most commonly encountered. Consequently, the turbulence type data of each route type largely reflects the characteristics of its dominant flight phases. The greater prevalence of CAT on long-haul operations also contributes to their higher observed intensities, given that CAT is generally associated with greater intensity than convective turbulence. Route type therefore does not appear to be an independent driver, but rather a proxy for turbulence frequency to specific flight phases and turbulence mechanisms.

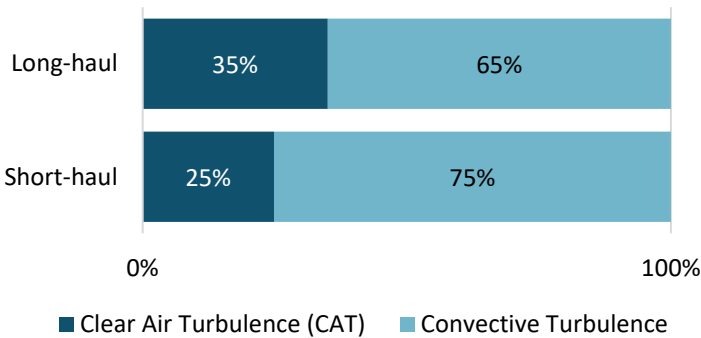


Figure 62 - Distribution of turbulence-related ECR occurrences by route type and turbulence type

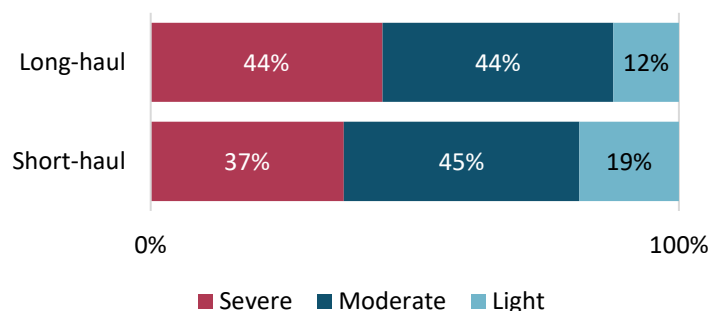


Figure 63 - Distribution of turbulence-related ECR occurrences by route type and intensity level

Additional factors that could play a role in the observed differences between short-haul and long-haul flights include inherent differences in the routes themselves (long-haul flights may cross jet streams or pass through turbulence hotspots, for example over mountainous regions in South America), and operational differences related to fuel weight management (short-haul flights may carry extra fuel to avoid refuelling at specific airports or to optimise turnaround times, and the difference in wing loading caused by additional weight could affect the magnitude of an aircraft's response to incoming turbulence, see Section 5.3).

Figure 64 shows the injury severity level distribution by route type. The data suggests that there is no significant difference in the likelihood and severity of injuries across the two route types.

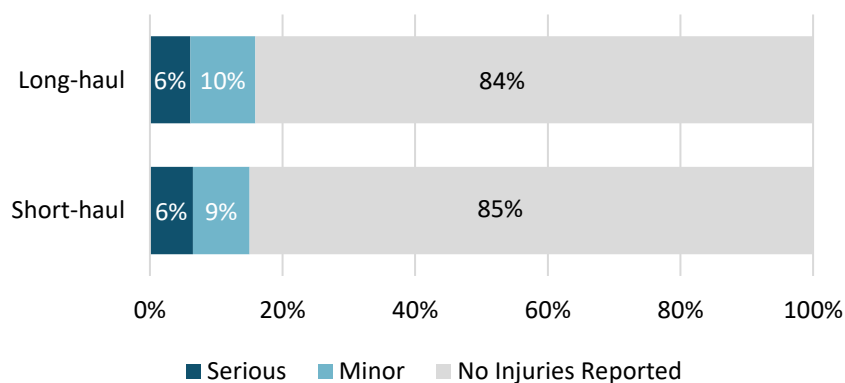


Figure 64 - Distribution of turbulence-related ECR occurrences by route type and injury severity level

5.8. Geographical distribution

The geographical location of the turbulence encounters is recorded in the ECR data and can also be extracted from the recorded flight data, taking into account the data governance constraints. The state/area of occurrence is a taxonomy attribute in the ECR data tied to an occurrence report and is used to determine the geographical location of the turbulence encounter. It should be noted that the attribute records the state or area where the occurrence took place, but not necessarily the exact location of the turbulence

encounter. Since all occurrences in the ECR dataset used in the present study are turbulence-related, the state/area of occurrence is assumed to be an adequate proxy for the location of the turbulence encounter.

Figure 65 shows the geographical distribution of turbulence-related ECR occurrences. The data are normalised by the total number of ECR occurrences reported in each state or area, and are presented as turbulence-related occurrences per 1,000 ECR occurrences. Normalisation by flight exposure was not applied because the resulting geographical distribution remained strongly influenced by differences in reporting practices between states. The selected approach instead indicates how often turbulence is reported relative to all safety occurrences submitted to the ECR within each state or area, thereby reducing the influence of differences in overall reporting volume. The results should therefore be interpreted as the relative prevalence of turbulence within the reported occurrence data, rather than as the actual prevalence of turbulence or rate of turbulence encounters per flight.

The higher occurrence rates appear in southern and south-eastern Europe, with Italy, Croatia, Greece and Iceland prominent, and the lowest rates are found around the Baltic. Several of the states with a higher rate of occurrence share features associated with turbulence. The southern and south-eastern states combine mountainous terrain with strong summer convective activity over the Mediterranean, while the North Atlantic jet-stream and the transatlantic corridor lie approximately over Iceland, where clear-air turbulence can be expected during cruise flight.

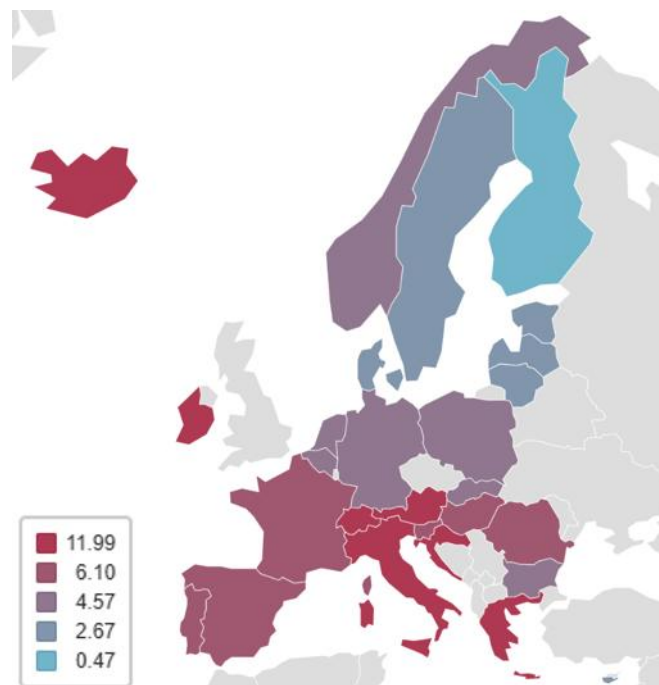
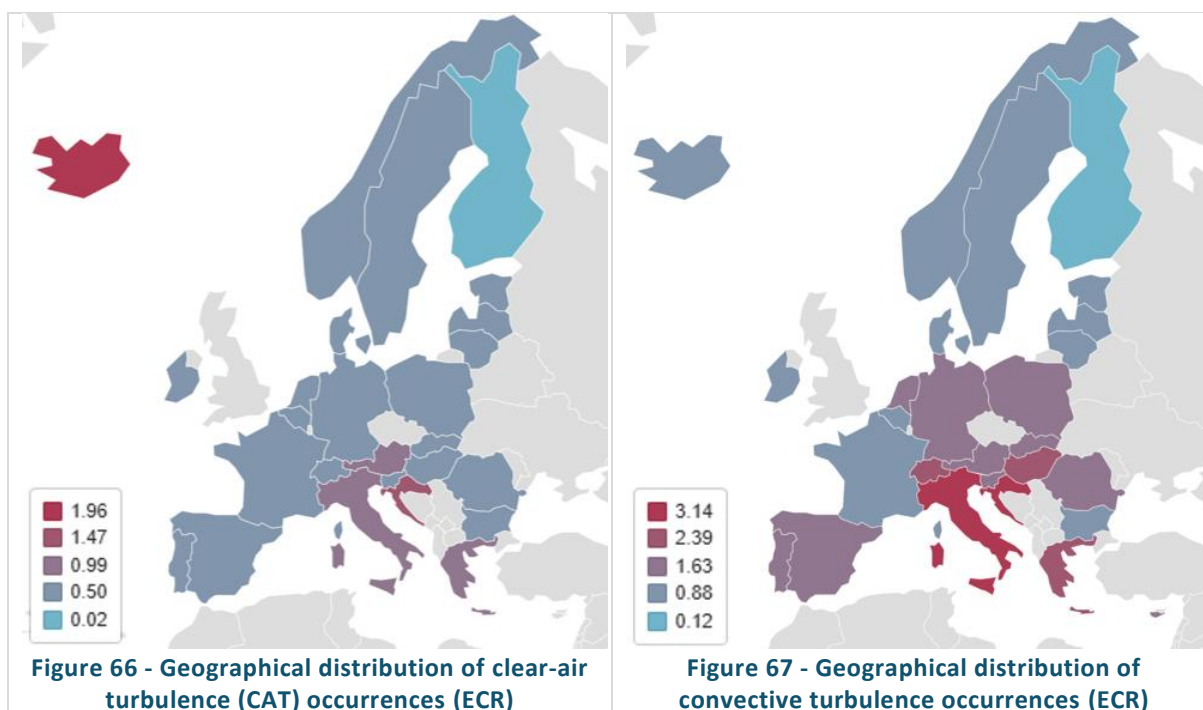


Figure 65 - Distribution of turbulence-related ECR occurrences by state area of occurrence, normalised per 1,000 ECR occurrences per state

Figure 66 and Figure 67 break the geographical distribution down by turbulence type. Occurrences associated with clear-air turbulence appear to occur mainly over Iceland and the North Atlantic and are less common across the Mediterranean, while the location of convective turbulence-related occurrences show precisely the opposite: Iceland is less prominent whilst the Mediterranean and southern Europe become more dominant. The geographical distribution therefore supports the turbulence-type characterisation described in Section 5.6.



The geographical distribution of turbulence episodes in the recorded flight data can also be investigated. However, due to the data governance constraints introduced in Section 3.2.6, the geographical information that can be presented is limited and provides limited additional value to the study. Nevertheless, for the sake of completeness, the geographical distribution of turbulence episodes in the recorded flight data is shown in Figure 68, distributed using H3 grid cells¹² and normalised per 1,000 flights. The grey cells represent areas where recorded flight data is available (irrespective of whether it includes turbulence episodes or not), while the coloured cells are those where turbulence is encountered and where there are sufficient flights performed by a sufficient number of operators to comply with the representativeness requirements of the DaGo rules (see Section 3.2.6). The vast amount of grey areas highlights the potential of future research. A more detailed geographical analysis based on recorded flight data could be performed as the D4S programme continues to evolve and incorporate data from additional stakeholders. It should be noted that the identification of a particular stakeholder in the visualisation reflects only the availability and

¹² H3 are divisions of the earth's surface based on a grid of hexagon-shaped cells with varying levels of granularity.

distribution of the recorded data and should not be interpreted as attributing any responsibility to that stakeholder for the turbulence events shown.

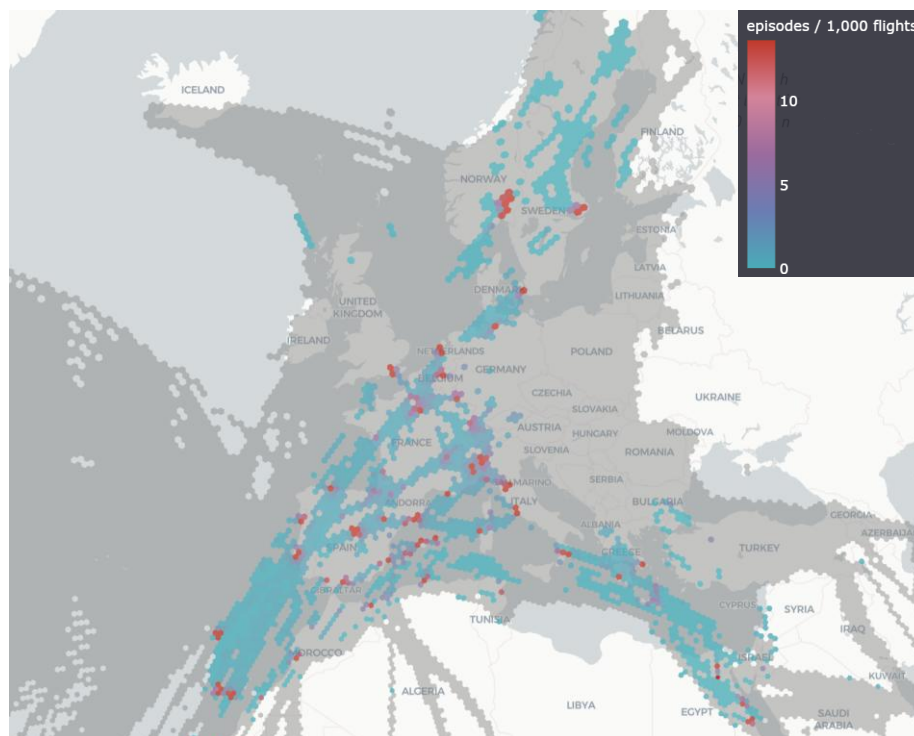


Figure 68 - Distribution of turbulence episodes by H3 index, normalised per 1,000 flights¹³ (recorded flight data)

The data of Figure 68 shows that turbulence episodes are concentrated around some of the major European airports (Paris, Amsterdam, Madrid, Barcelona, Lisbon), consistent with the concentration of episodes at lower altitudes in the recorded flight data discussed in Section 5.3.

To remove the effect of the low altitude skew in the recorded flight data, Figure 69 presents the geographical distribution of turbulence episodes of moderate and severe intensity identified during the cruise phase. These turbulence episodes appear to be concentrated in several hotspots, two of which broadly correspond with the mountainous regions over the Pyrenees and the Alps. However, it must be noted that the data sample is limited due to DaGo constraints and therefore readers are advised against drawing strong conclusions from this data, considering as well that the available recorded flight data does not allow for a distinction between different types of turbulence or for determining whether a specific association of turbulence with mountainous terrain exists in the dataset.

¹³ Normalisation is performed based on total number of flights within each H3 index.

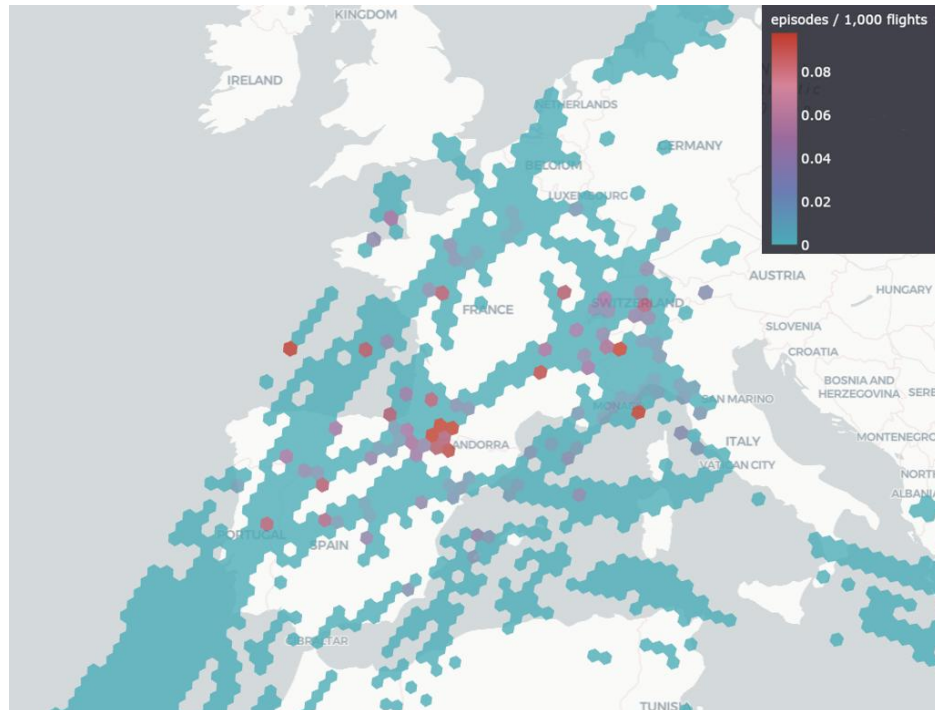


Figure 69 - Distribution of moderate and severe turbulence episodes during cruise by H3 index, normalised per 1,000 flights. Normalisation is performed based on total number of flights within each H3 index

5.9. Seasonality

To conclude the characterisation of turbulence events, this section considers the seasonality of the identified turbulence encounters both in the ECR dataset and the recorded flight data. In both cases, the seasonality analysis is restricted geographically to the Northern Hemisphere to ensure a consistent definition of the seasons across the dataset. Including flights from both hemispheres would combine opposing seasonal cycles, potentially masking underlying seasonal patterns in turbulence occurrences.

Figure 70 shows the seasonal variation of turbulence occurrences in the ECR data sample, normalised per 1,000 flights to account for seasonal variations in traffic volume. The frequency of the total turbulence-related occurrences peaks during winter, from December till February, with a second smaller peak during summer. The frequency of occurrences involving injury has a stronger peak in the summer period compared to the total set. The peak observed in the summer period for occurrences with injuries is not reflected in the seasonality trend of the total dataset of occurrences due to the limited sample size of occurrences with injuries (approximately 15% of the total, as discussed in Section 5.4).

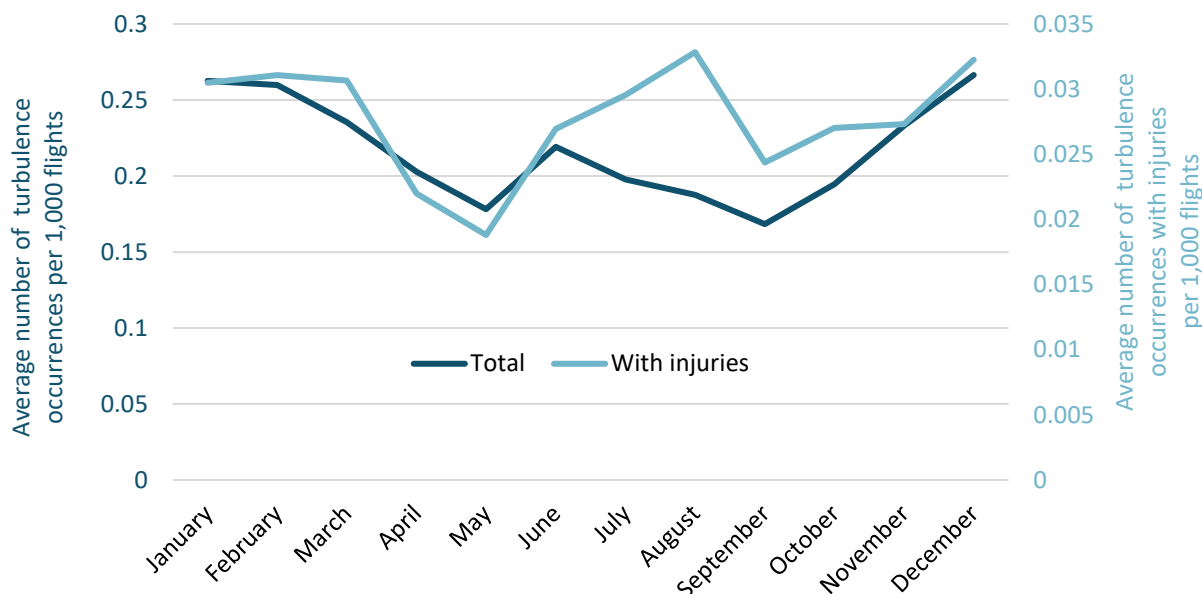


Figure 70 - Seasonality of frequency of turbulence-related ECR occurrences (total and with injuries).
Note the dual vertical axis

Figure 71 and Figure 72 show the seasonality of the turbulence-related occurrences in the ECR dataset by turbulence type, in percentage (Figure 71) and normalised per 1,000 flights (Figure 72). The two types of turbulence show contrasting seasonal cycles. Convective turbulence frequency is higher in summer, consistent with the seasonal cycle of atmospheric convection [30], whereas clear-air turbulence peaks during winter, in line with the stronger jet streams during winter [31]. The contrasting seasonality persists after exposure normalisation: the convective turbulence rate (per flight) increases approximately with a factor of three from winter to summer, while the CAT rate increases roughly by a factor of two from summer to winter. One caveat applies to these figures: the data for the winter months contain relatively more occurrences with unreported turbulence type. The distribution of these unreported occurrences between convective turbulence and clear-air turbulence (CAT) is unknown and therefore cannot be accounted for in the seasonal comparison. Although occurrences that lack a turbulence type classification are also present during the summer months, their greater proportion in winter introduces additional uncertainty into the contribution of the two turbulence types to the observed seasonal patterns.

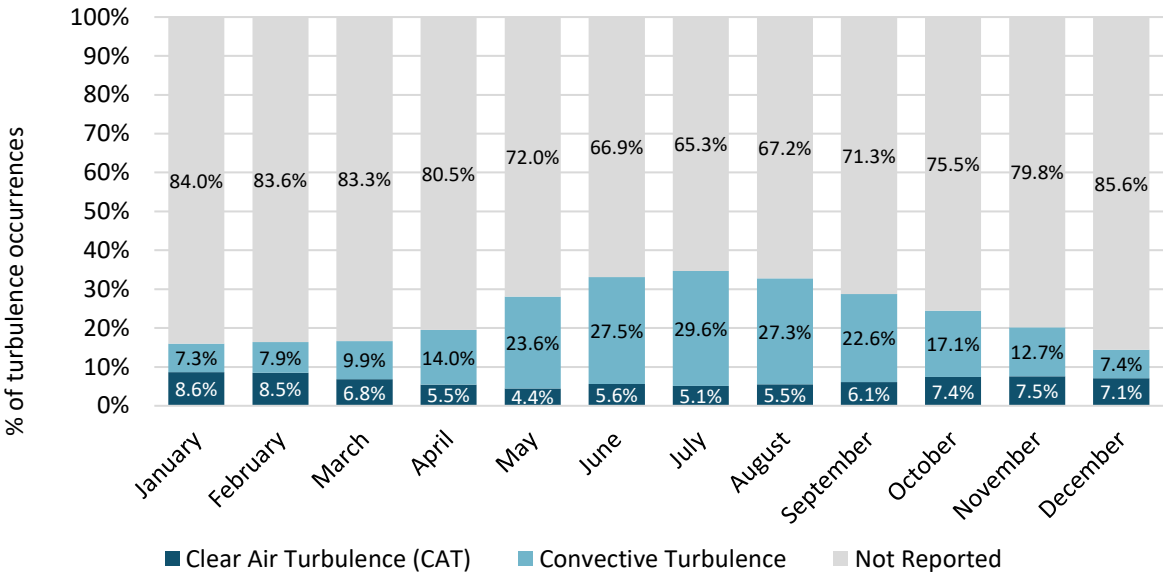


Figure 71 - Seasonality of turbulence-related ECR occurrences by turbulence type

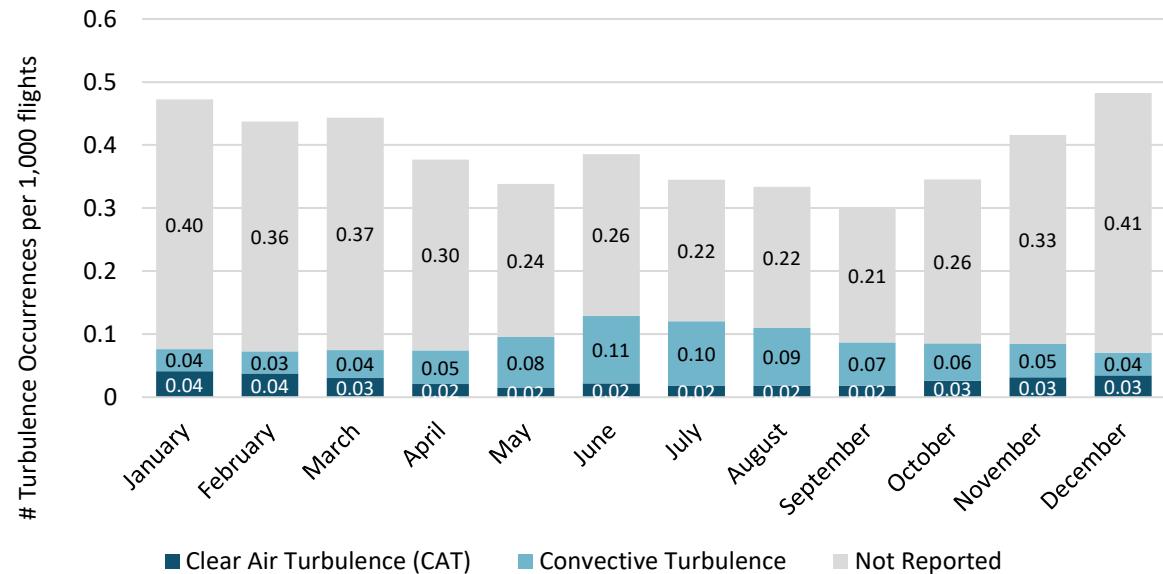


Figure 72 - Seasonality of turbulence-related ECR occurrences by turbulence type, per 1,000 flights

Figure 73 shows the seasonality of the turbulence-related ECR occurrences broken down by intensity level. Light intensity occurrences show no apparent seasonality, likely due to their limited sample size: light intensity turbulence encounters are generally not reported to the ECR and therefore strongly underrepresented in the ECR data sample. Turbulence-related occurrences of moderate and severe intensity level show a similar pattern consistent with the general trend observed in Figure 70, with a higher number of occurrences reported throughout the winter months and a secondary but smaller peak in June. It is worth noting that the winter peak is particularly pronounced for the moderate intensity occurrences,

located in December and January, whereas the frequency of occurrences of severe intensity peaks in February.

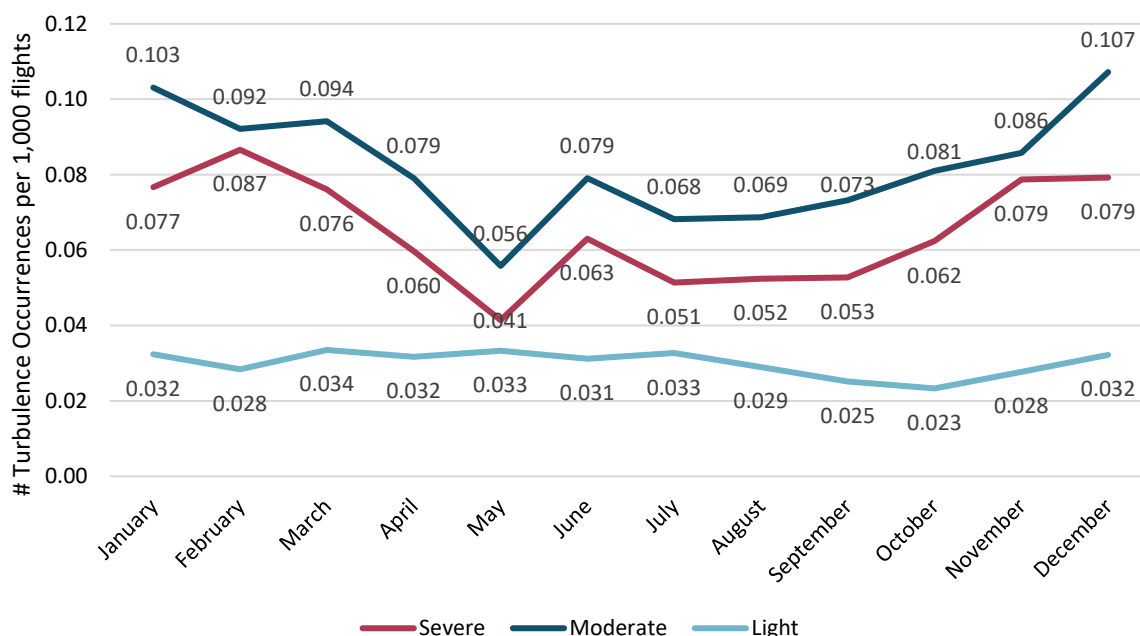


Figure 73 - Seasonality of turbulence-related ECR occurrences by intensity level, per 1,000 flights

Figure 74 to Figure 77 show the seasonal variation of turbulence episodes in the recorded flight data, normalised per 1,000 flights. Figure 74 shows the aggregated seasonal variation for all turbulence episodes. Figure 75, Figure 76, and Figure 77 show the seasonal variation of the turbulence episodes for each intensity level (light, moderate, and severe intensity, respectively).

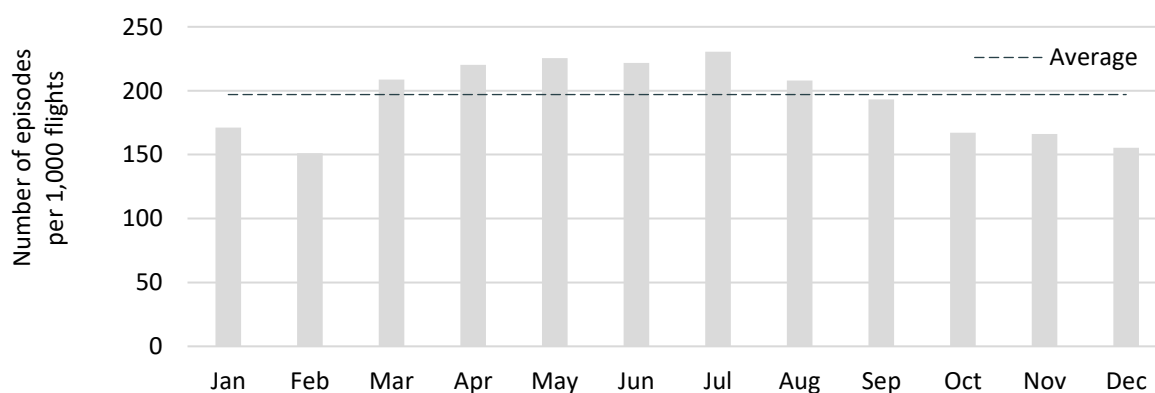


Figure 74 - Seasonal distribution of turbulence episodes per 1,000 flights (recorded flight data)

Figure 74 shows the frequency of episodes is highest during summer, rising from a minimum in February to a maximum in July. Light intensity episodes in the recorded flight data exhibit a higher rate of occurrence during summer. In general, the aggregated seasonality of Figure 74 is almost identical to that of Figure 75 due to the predominance of light intensity episodes in the recorded flight data (see Section 5.2.2).

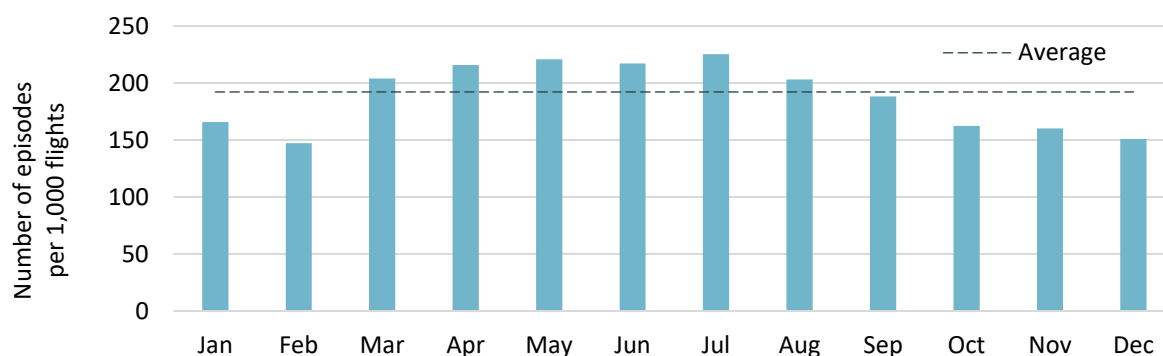


Figure 75 - Seasonal distribution of turbulence episodes of light intensity per 1,000 flights

The turbulence episodes of moderate and severe intensity level show a different seasonal trend. Severe episodes in particular show higher frequency during the winter months, with lower rates than average during spring months, in agreement with the ECR data. Much like the comparison of the overall rates presented in Section 5.2.1, the data indicates that in terms of their seasonal behaviour the two data sources differ strongly at light intensities but show increasing agreement for moderate and a comparable trend at severe intensity.

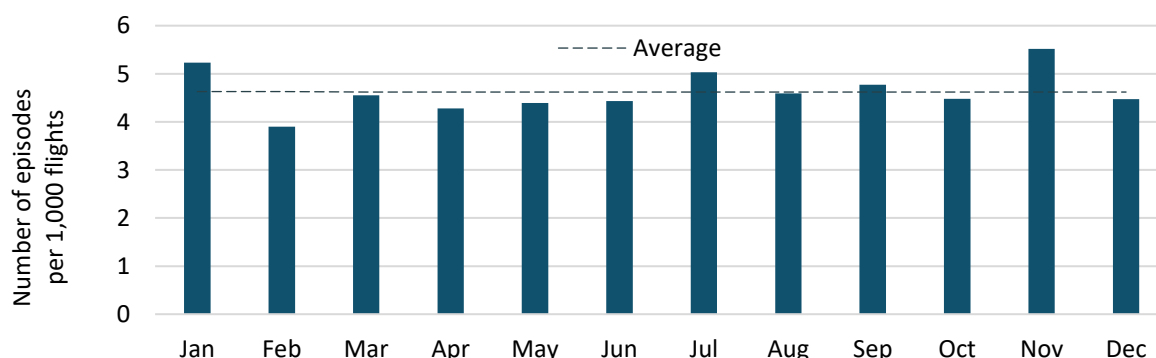


Figure 76 - Seasonal distribution of turbulence episodes of moderate intensity per 1,000 flights (recorded flight data)

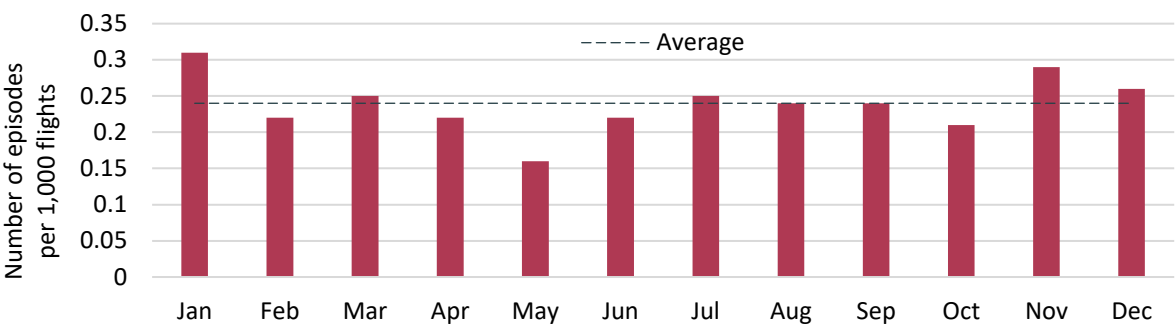


Figure 77 - Seasonal distribution of turbulence episodes of severe intensity per 1,000 flights (recorded flight data)

6 ANALYSIS OF CONSEQUENTIAL EVENTS AND SAFETY-BARRIER PERFORMANCE

The preceding chapter has characterised turbulence occurrences. This chapter focuses on the analysis of consequential events and the performance of the relevant safety barriers. First, Section 6.1 presents the consequential events of the turbulence encounters which may involve airline, ATC and crew actions through an analysis of the turbulence-related ECR occurrence data. Then, a complimentary analysis of consequential events using recorded flight data is presented in Section 6.2. Finally, a barrier performance analysis is done with the support of a bow tie framework applied to turbulence, described in section 6.3.

6.1. Consequential events in the ECR dataset

The analysis of consequential events is based on the turbulence-related ECR occurrence because we can benefit from the enhancement of the Event Type attribute completed during the data-quality improvement phase during data processing. That enhancement combined the Event Type information already available in the structured ECCAIRS2 data with information extracted from occurrence narratives. For Event Type, the LLM assigned standardised ECCAIRS2 values from a study-specific subset of operational and safety events relevant to turbulence and returned all relevant events identified in a report in chronological order, as explained in Section 4.1.6.

The source Event Type values are standard ECCAIRS2 taxonomy labels. Their official definitions can be consulted in the ECCAIRS2 Taxonomy Browser [3]. For the present analysis, these source values were mapped into broader, study-specific consequential-event groups so that related taxonomy values could be treated consistently and presented using clearer analytical labels. All the events analysed in this section were identified within occurrences previously classified as involving turbulence. They are therefore treated as events associated with the reported turbulence encounter. However, their presence in the same occurrence does not, by itself, demonstrate that turbulence directly caused each event.

The groups cover overspeed condition, aircraft upset, level bust, injured person on board, aircraft damage, aircraft damage explicitly associated with dynamic g-loads, loss of separation, reduction in safety margins and operational consequences. Operational consequences include changes or disruptions to the planned operation, such as diversion, return, delay, go-around, missed or precautionary landing, unstable approach, and route or clearance deviation. The group definitions and detailed mapping are provided in Table 10.

Table 10 - Consequential event groups used in the assessment

Consequential event	Definition
Overspeed condition	An exceedance of, or deviation towards, an applicable maximum operating or configuration-speed limitation. It includes exceedance of or movement towards VMO or MMO, activation of an overspeed warning, and exceedance of flap, slat or landing-gear speed limits. Generic speed-deviation values were included only where the occurrence context indicated a high-speed condition rather than a low-speed deviation.

Aircraft upset	An unintentional deviation from the intended flight path, aircraft attitude or commanded profile. It includes reported deviations in bank or roll, heading, pitch, altitude or intended airspeed, as well as uncommanded aircraft movement. This is a broad ECR occurrence classification and should not be interpreted as requiring the parameter-based upset thresholds applied to the recorded flight data.
Level bust	A deviation from an assigned flight level or altitude. This is retained separately from the broader aircraft upset group because it represents a specific deviation from an ATC altitude or Flight Level clearance.
Injured person on board	An injury, illness, medical emergency or incapacitation affecting a passenger, cabin crew member or flight crew member.
Aircraft damage	Reported aircraft damage or an aircraft condition classified as a possible indication of damage. The source taxonomy includes a combined value covering damage associated with turbulence, hail or lightning. This value was included only when reported within a selected turbulence occurrence, but the available classification does not always allow the damage to be attributed specifically to turbulence rather than to another associated weather phenomenon. Reported vibration, buffet or abnormal smells were treated as possible damage-related indications and not necessarily as confirmation of structural damage.
Aircraft damage due to dynamic g-loads	A specific subgroup covering ECCAIRS2 values that explicitly associate reported aircraft damage with dynamic loading. It is retained separately because these more specific values are relatively new and are not used consistently across the dataset. The subgroup may overlap with the broader aircraft-damage group and should not be added to it when calculating an overall aircraft-damage total.
Loss of separation	A loss or degradation of separation between aircraft. It includes loss of separation, separation minima infringement and loss of separation associated with a level bust or adjusted flight path.
Reduction in safety margins	An event indicating that the occurrence moved closer to an unsafe aircraft or operational state without necessarily producing a more specific consequence. It includes operation outside aircraft limitations, excessive or insufficient climb/descent rates and navigation-track errors.
Operational consequences	A change, disruption or recovery action affecting the planned operation, including diversions, returns, delays, cancellations, aircraft changes, go-arounds, missed or precautionary landings, unstable approaches and route, clearance or procedure deviations.

Each group is reported as the proportion of turbulence-related ECR occurrences in which that consequence was identified. The groups are not mutually exclusive: one occurrence may include several consequences affecting different safety dimensions. The consequential events identified are presented in Figure 78. Overspeed is the most frequent consequence, reported in about a quarter of turbulence-related occurrences. It is followed by injuries to persons on board, aircraft upset and operational consequences such as diversions (which are further reviewed in Appendix D.1). Aircraft damage and loss of separation are least frequently reported.

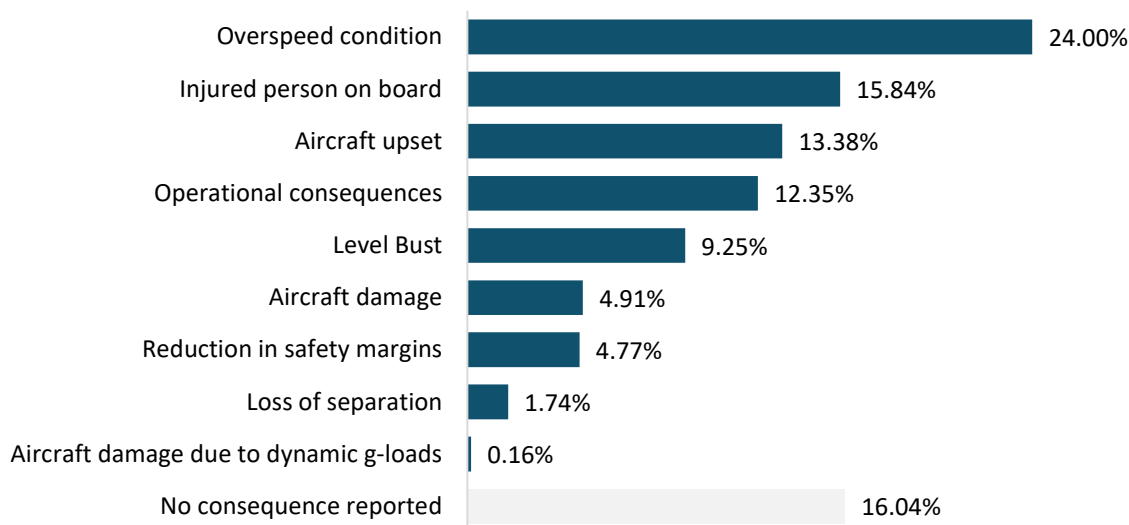


Figure 78 - Consequential events of turbulence-related ECR occurrences

No consequence was recorded in approximately 16% of the reported turbulence-related occurrences. This figure applies only to occurrences captured in the ERC and should not be interpreted as representative of turbulence encounters in general, as turbulence encounters without any consequences are less likely to be reported to the ECR.

6.2. Consequential events in the recorded flight data

Following the identification and quantification of the consequences of turbulence encounters in the ECR data sample, this section provides a more detailed analysis of selected consequential events using recorded flight data. The scope is constrained by the information available in these recordings: only events that can be detected and characterised from the recorded flight parameters are included, rather than all consequences identified in the ECR sample. Within this constraint, the selection also considers the relevance of these events to the findings of the previous section.

The consequential event categories considered for the analysis using recorded flight data are therefore based on the preceding analysis of ECR data and the technical feasibility for identification in the recorded flight data. Since only a subset of flight data parameters are decoded and available in the set of recorded flight data, the analysis is limited to events for which suitable parameters and reliable detection criteria can be defined. The selected events are subsequently characterised within the recorded flight data sample, with aggregate patterns and trends compared to the findings from the analysis of ECR data (see previous section), provided that the event definitions and underlying data are sufficiently comparable.

After completing this process, the consequential events analysed in the recorded flight data sample include:

- Autopilot disengagement (disconnect)
- Overspeed

- Aircraft upset
- TCAS RA
- High loads, which distinguish between:
 - Flight envelope protection limits
 - Passenger comfort and safety

6.2.1. Methodology

This section provides an overview of the implemented methodology for each consequential event analysed by means of flight data.

6.2.1.1. *Autopilot disengagement*

Pilot interaction during turbulence cannot be directly evaluated because the available recorded flight data does not include control inputs or flight control surface deflections. The analysis therefore focuses on the aspects of aircraft automation that can be directly derived from the data, primarily autopilot engagement.

The methodology for detecting autopilot disengagements events caused by turbulence episodes is the following:

- Identifying autopilot disengagements occurring during turbulence episodes, defined as transitions of the decoded autopilot engagement parameter from 1 (engaged) to 0 (not engaged).

However, the available data does not indicate whether a disengagement was initiated manually by the flight crew or triggered automatically by the aircraft systems. Consequently, events identified as autopilot disengagements include these two possibilities.

6.2.1.2. *Overspeed*

Overspeed events were selected as they represent the most frequently identified consequential event in the ECR data analysis, making them particularly relevant for further investigation by means of flight data. In order to achieve a robust analysis with the available parameters in the recorded flight data, the study focuses on exceedances of the aircraft certified maximum operating speed limits, namely the Maximum Operating Velocity (VMO) and the Maximum Operating Mach Number (MMO).

The applied methodology for detecting overspeed events caused by turbulence episodes is the following:

- Retrieve the applicable MMO/VMO values for the corresponding aircraft type.
 - The certified VMO and MMO values for the aircraft types included in the recorded flight data are summarised in Table 11.
- Compare the recorded airspeed and Mach number throughout the turbulence episode with the corresponding VMO and MMO limits.

Table 11 – MMO and VMO values by aircraft family [32]

Aircraft Family	MMO	VMO (kt)
A320	0.82	350
A330	0.86	330
B737	0.82	340

6.2.1.3. Aircraft upset

Aircraft upset was selected because of its relevance in the ECR data analysis. However, the definition of aircraft upset used in that analysis encompasses a wide variety of situations, many of which cannot be directly identified from recorded flight data. For this reason, the analysis of recorded flight data for this event is intentionally limited to changes in aircraft attitude.

The methodology for detecting aircraft upset events caused by turbulence episodes is the following:

- Evaluate maximum roll and pitch angles reached by the aircraft during the turbulence episode.
- Compare the recorded attitude values with a set of predefined thresholds to identify aircraft upset events.

The thresholds adopted in this study are summarised in

Table 12 and are based on the aircraft upset definitions published by EASA [33] and the FAA [34].

Table 12 – Bounds for the definition of aircraft upset and onset of aircraft upset

Condition	Roll [°]	Pitch [°]
Onset of Aircraft Upset	$37 < \text{roll} < 45$	-
Aircraft Upset	$\text{roll} > 45$	$\text{pitch} > 25$ $\text{pitch} < -10$

In addition to the standard aircraft upset thresholds, an onset of aircraft upset category has been introduced. Although a roll angle within this range would not formally be classified as an upset condition, these attitude values lie outside the normal operational envelope and may therefore represent the initial stages of an upset. Including this category allows the analysis to capture significant aircraft attitude deviations that fall below the regulatory upset thresholds.

6.2.1.4. TCAS RA

TCAS RA (Traffic Alert and Collision Avoidance System Resolution Advisory) events were selected because a validated dataset from previous Data4Safety studies was available, supporting consistent implementation and comparison with earlier work. In the ECR data analysis, a loss of separation is a relevant consequential event, while TCAS RA events provide an objective indicator of those situations in which aircraft separation may have been compromised.

The analysis first identifies flights containing both a TCAS RA event and a detected turbulence episode. A TCAS RA event is associated with an episode when its start time falls:

- Between the start and end of the turbulence episode; or
- Within one minute after the episode, capturing alerts potentially related to delayed operational effects.

6.2.1.5. High load factor episodes

High load factor episodes represent the largest aircraft responses to turbulence and may provide indirect evidence for several consequential events identified through the analysis of the ECR data sample, including passenger injuries, weight-off-seat events¹⁴ and aircraft damage.

The analysis therefore identifies turbulence episodes with exceptionally high positive or negative load factors using the raw aircraft's Z-axis acceleration signal (raw Nz), as it represents the total load experienced by the aircraft and occupants during the turbulence episode.

Two sets of thresholds were established based on different criteria. The two criteria are explained below, and their respective thresholds are presented in Table 13.

- **Flight envelope protection limits.** The first criterion is based on Airbus' aircraft normal law protection limits, which prevent the aircraft from exceeding load factors of +2.5 g and -1.0 g [35].
- **Passenger comfort and safety.** The second criterion is based on physiological considerations, with thresholds defined at 0.0 g, corresponding to weight-off-seat conditions, and +2.0 g, representing a negative and high positive g-load associated with significant passenger discomfort.

A turbulence episode is classified as a high load factor event if the Nz exceeds any of the thresholds defined above at least once during the episode.

Table 13 – Bounds for the definition of high load consequential events¹⁵

High Load Classification	Lower Bound [g]	Upper Bound [g]
Passenger discomfort	0.0	2.0
Flight envelope protection limits	-1.0	2.5

6.2.2. Results

¹⁴ A weight-off-seat event refers to a condition in which the negative g-loads reduce the effective load on a passenger sufficiently for them to partially or completely lose contact with their seat.

¹⁵ The bounds correspond to the raw Nz signal (unfiltered). A high load event is identified when the raw Nz signal falls below the lower bound or above the upper bound.

Although severe turbulence represents only 0.1% of all turbulence episodes, it is disproportionately associated with consequential events. Across nearly all analysed consequential events, the occurrence rate of consequential events increases markedly with the intensity level of the aircraft's response to turbulence. Depending on the consequence, severe intensity produces occurrence rates between one and two orders of magnitude greater than light intensity. This observation can be seen in Figure 79 below, which uses logarithmic scale to represent the frequency of each consequence depending on the intensity level.

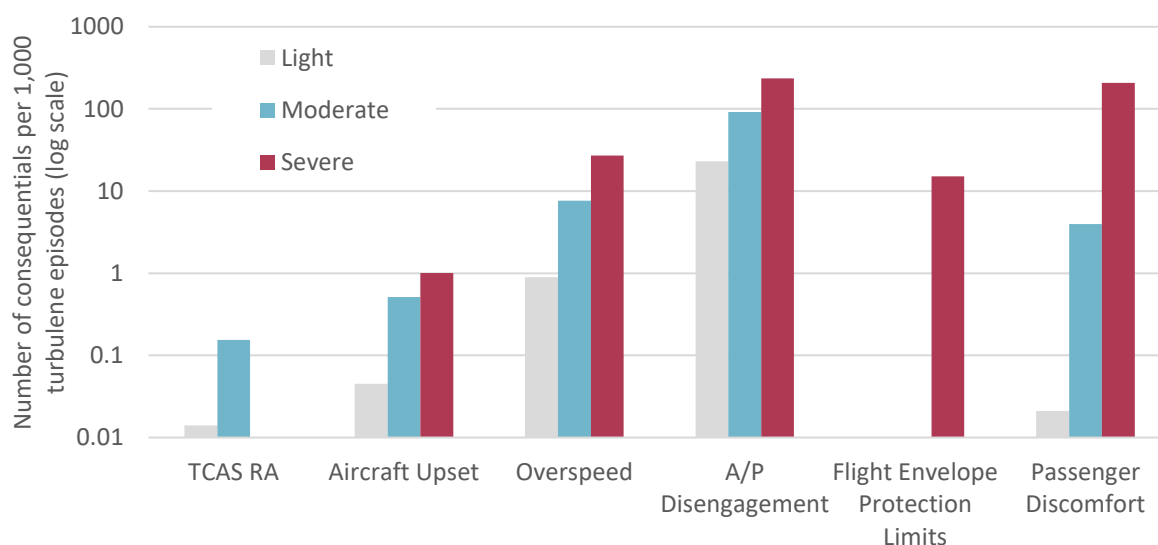


Figure 79 - Rate of consequential events per 1,000 turbulence episodes, by intensity level (logarithmic scale)

Autopilot disengagements are the consequential events with the highest observed frequency, in the order of 100 events per 1,000 episodes of severe intensity and closer to 10 events per 1,000 episodes of light intensity. Loads capable of causing passenger discomfort have a similar frequency to autopilot disengagements for episodes of severe intensity, while high loads causing exceedances of flight envelope protection limits are less common. Overspeed events exhibit a rate of around 27 per 1,000 turbulence episodes for severe intensity. Aircraft upsets have comparable rates across moderate and severe intensities, with the rate falling sharply to 0.045 for light events. Finally, TCAS RA events are the least likely to occur, with an observed frequency in the order of 0.1 events per 1,000 episodes of moderate intensity and an order of magnitude less for those of light intensity.

Another interesting perspective is to analyse which consequential events occur simultaneously during the same turbulence episode. Episodes involving multiple consequential events may indicate a higher level of operational risk, as they represent turbulence encounters associated with a more pronounced aircraft response but also increased likelihood of aircraft upset, overspeed, or passenger discomforts/injuries. Figure 80 presents the rate of occurrence of each combination of consequential events, together with the overall occurrence rate for each individual consequence, expressed per 1,000 turbulence episodes. The combinations are ordered from most to least frequent (from left to right, upper bars). The coloured circles indicate the consequential events included in each combination, while the left-hand side of the figure shows the aggregated occurrence rate for each individual consequential event, irrespective of whether it occurred alone or in combination with other consequential events.

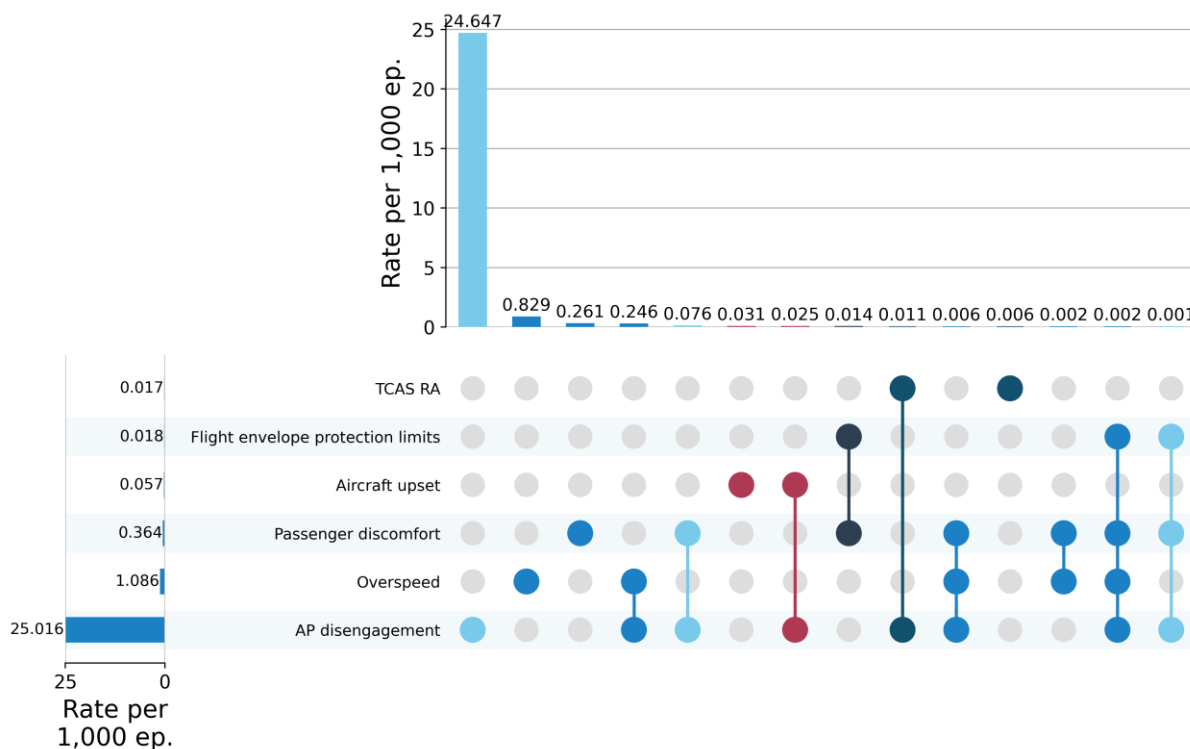


Figure 80 - Rate of consequential events by 1,000 turbulence episodes. Vertical bars show rates of combined consequential events, bars on the left show aggregated rates per consequential type

The analysis shows that most consequential events occur in isolation rather than in combination, indicating that turbulence rarely leads to cascading operational effects. By far the most frequent isolated consequential event is autopilot disengagement, occurring at approximately 25 events per 1,000 turbulence episodes, followed by overspeed by 1 event per 1,000 turbulence episodes. The most common multi-event combination is autopilot disengagement together with overspeed (0.25 events per 1,000 turbulence episodes). This co-occurrence is assumed to reflect an operational relationship between the two events; however, the available parameters in the recorded flight data do not indicate whether the autopilot was disengaged manually by the flight crew or automatically by the aircraft systems. Aircraft upsets, TCAS Resolution Advisories, and exceedances of flight envelope protection limits are comparatively rare, with the latter occurring exclusively during severe turbulence episodes. Overall, the results indicate that the most common operational consequences of turbulence encounters are isolated autopilot disengagements and overspeed events, while combinations of multiple consequential events remain exceptional.

Autopilot disengagement – Focusing on the most common consequential event, Figure 81 below shows the distribution of autopilot disengagements by flight phase. The majority of events occur during descent (62.9%), followed by the approach phase (27.7%). Climb, cruise, and initial climb account for a much smaller proportion of the total. This distribution is consistent with normal flight operations. During the descent and approach phases, pilots routinely disconnect the autopilot to continue the flight manually, particularly during the final stages of the approach. Consequently, not all autopilot disengagements identified in the

vicinity of turbulence should be interpreted as being directly caused by the turbulence itself. Rather, the higher occurrence rate in these phases is likely influenced by the greater background frequency of autopilot disengagements during normal operations. Additionally, the general trend towards turbulence episodes at lower altitudes present in the overall dataset in recorded flight data is also likely a contributing factor for the distribution observed in Figure 81, although it cannot account by itself for the fact that descent and approach are responsible for approximately 90% of turbulence episodes.

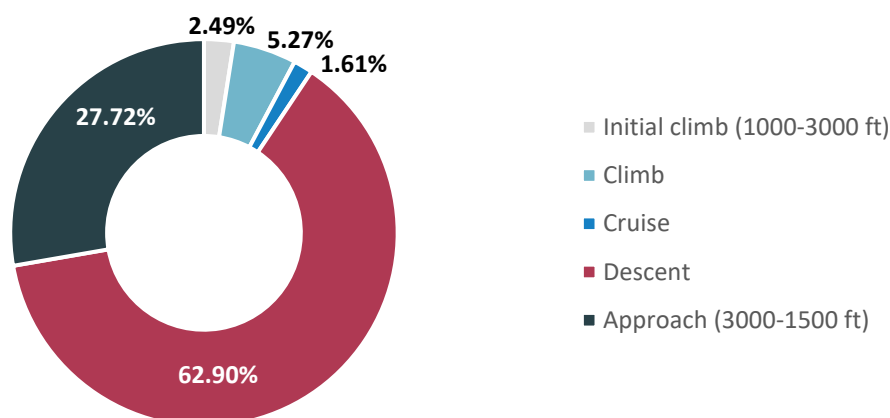


Figure 81 - Breakdown of autopilot disengagements by flight phase

Focusing on the number of disengagements per episode, Figure 82 shows the number of autopilot disengagements per turbulence episode among episodes involving at least one disengagement. A single disengagement occurs in 74.75% of these episodes, while 22.95% contain two, 1.18% contain three and 1.12% contain four or more. Taken together, 25.25% of these episodes involve repeated disengagements, indicating that the autopilot did not cope well turbulences in one quarter of turbulence episodes. This finding warrants closer examination of the autopilot's ability to remain engaged during turbulence, and its ability to surpass the turbulence when re-engaged.

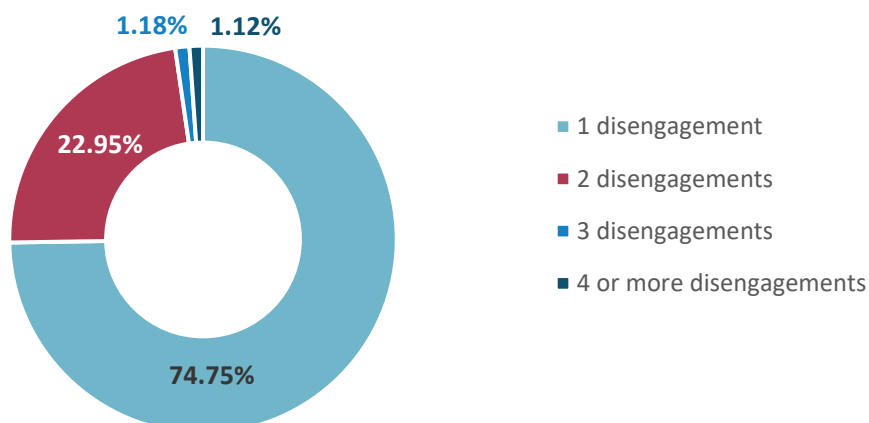


Figure 82 - Breakdown of autopilot disengagements by number of disconnections

Overspeed – A total of 899 overspeed events were identified during turbulence episodes. Although most occurred during light turbulence due to its much higher frequency of occurrence in the data sample, the normalised occurrence rate increased markedly with the intensity level, reaching 27.2 events per 1,000 severe turbulence episodes, compared with 7.6 for moderate and 0.9 for light turbulence. Overspeed events occurred predominantly during the cruise phase (see Figure 83), where aircraft operate close to their maximum operating Mach number (MMO). The analysis of cruise overspeed events therefore focuses on Mach number and, in particular, on the change in Mach number associated with the turbulence episode.

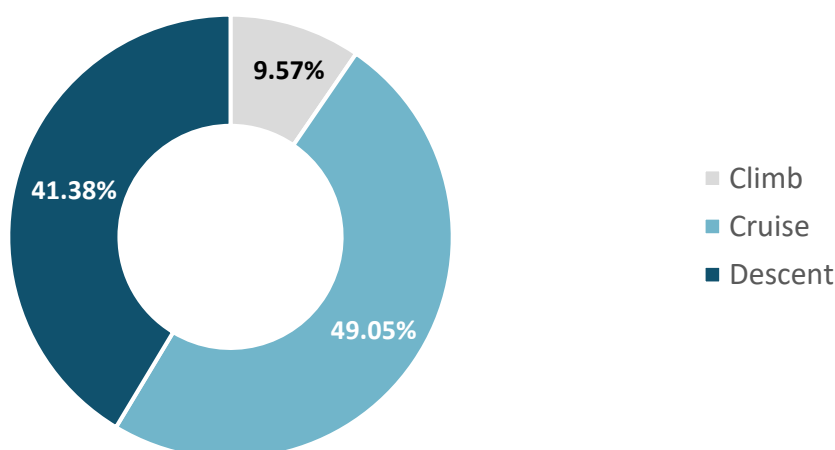


Figure 83 - Breakdown of overspeed events by flight phase

Figure 84 shows the probability density of the average Mach number during the 1-minute preceding a turbulence episode (left), the average Mach number during the turbulence episode (centre), and the maximum Mach number reached during the episode (right), for light and moderate/severe intensity levels. Moderate and severe intensities are associated with larger peak Mach values than light intensity, while having lower average operating Mach numbers. The lower average Mach values, both during the minute preceding the episodes and during the episodes, are consistent with aircraft being operated at reduced

speeds when turbulence is anticipated or encountered, providing greater margin to the applicable speed limit. To further characterise the speed excursions associated with turbulence, the change in Mach number was calculated as the difference between the average Mach number during the one-minute period preceding the turbulence episode and the maximum Mach number reached during the episode. The resulting distributions are presented Figure 85. A clear shift towards larger Mach increases is observed for moderate and severe intensity levels compared with light. The average Mach increase is 0.054 for moderate and severe intensities, compared with 0.045 for light intensity. Thus, moderate and severe intensity levels are associated, on average, with a Mach increase approximately 0.009 higher than that observed for light responses. These results indicate that the circumstances associated with overspeed events differ according to the intensity level. For light intensities, overspeed events generally occur when the aircraft is already operating relatively close to its applicable speed limit. For moderate and severe intensities, aircraft are generally operating at lower entry Mach values, but the larger Mach excursions observed during the episode can reduce this speed margin sufficiently for an overspeed event to occur.

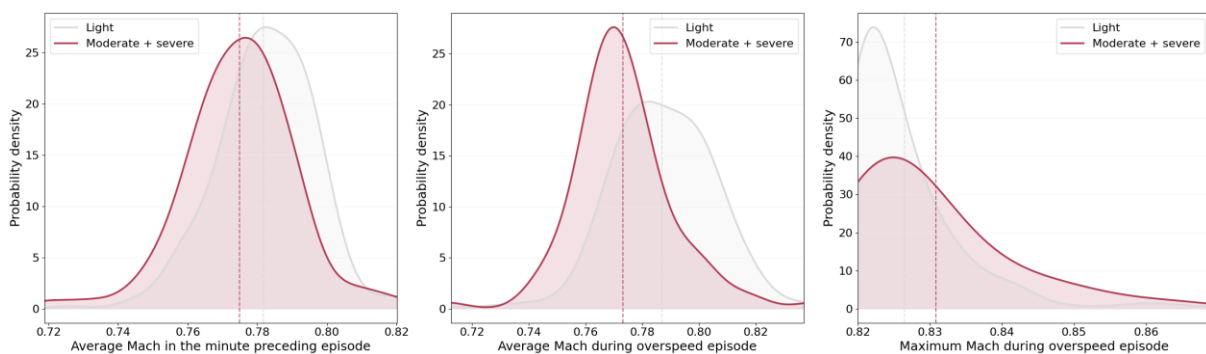
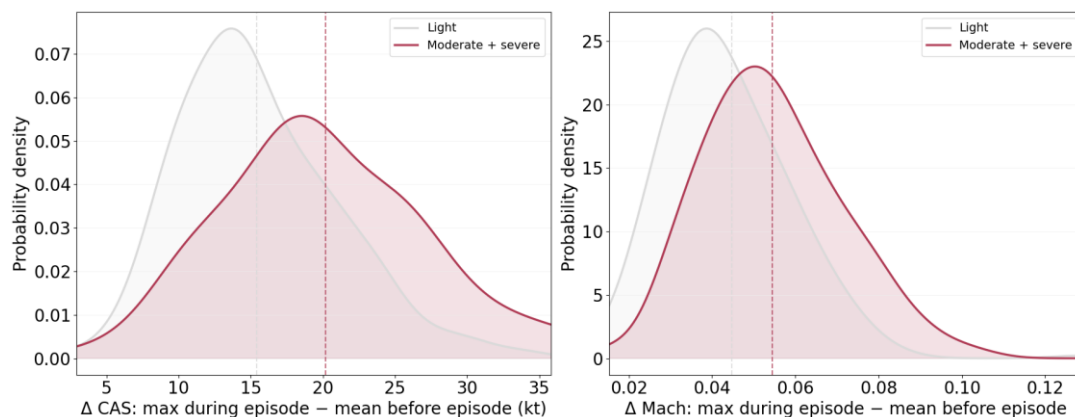


Figure 84 - Probability density of average Mach in the minute preceding episodes, average Mach during overspeed events, and maximum Mach during overspeed episodes, by intensity level (light and moderate+severe)¹⁶



¹⁶ Only cruise overspeed events shown.

Figure 85 - Probability density of the increase in calibrated airspeed (CAS) and Mach number during overspeed events¹⁷

Aircraft upset – The analysed aircraft upset events in this study remain uncommon across the analysed dataset, although their occurrence rate increases substantially with the intensity level. Most events consist of isolated pitch-up or bank-angle exceedances (Figure 86), while combinations of multiple upset criteria are rare. The highest number of upsets occur during climb and descent (Figure 87), reflecting the greater manoeuvring activity during these flight phases, where turbulence-induced disturbances may occur while the aircraft is manoeuvring, potentially resulting in attitude excursions beyond the defined thresholds. Additionally, and similarly to the distribution of autopilot disengagements, this may also be partly affected by the general skew towards lower altitudes of turbulent episodes in the recorded flight data.

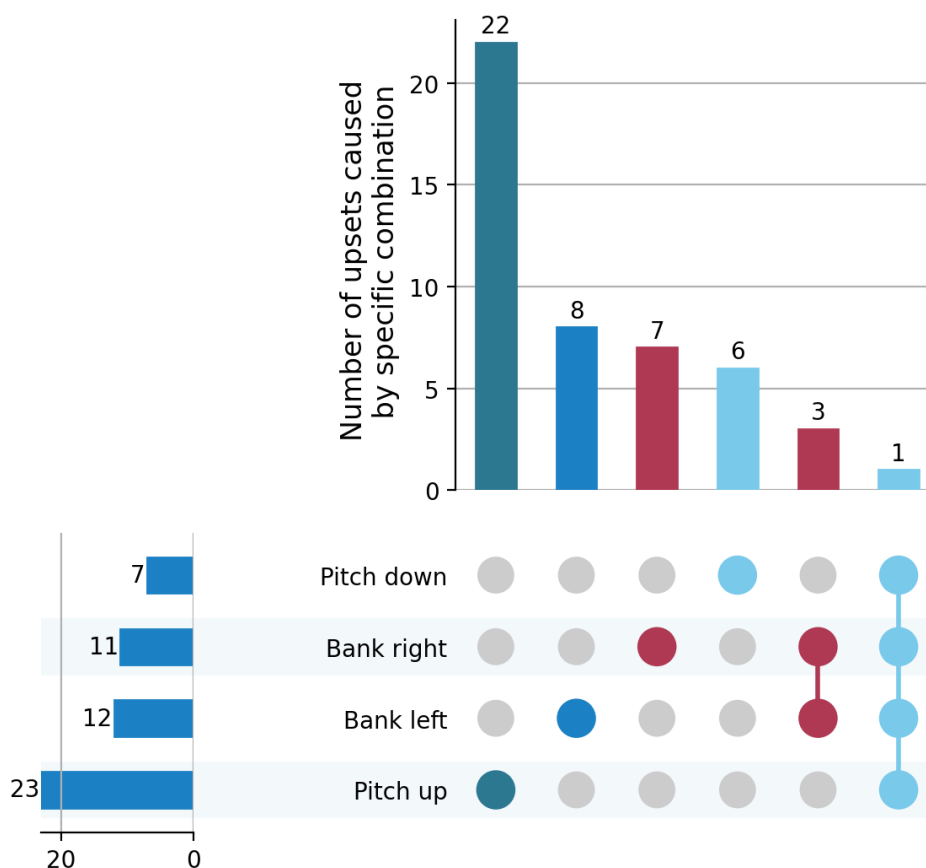


Figure 86 – Types of aircraft upset. Vertical bars show number of upsets caused by each combination of attitude excursion. Lateral bars show total number of upsets by type of aircraft upset

¹⁷ Only cruise overspeed events shown.

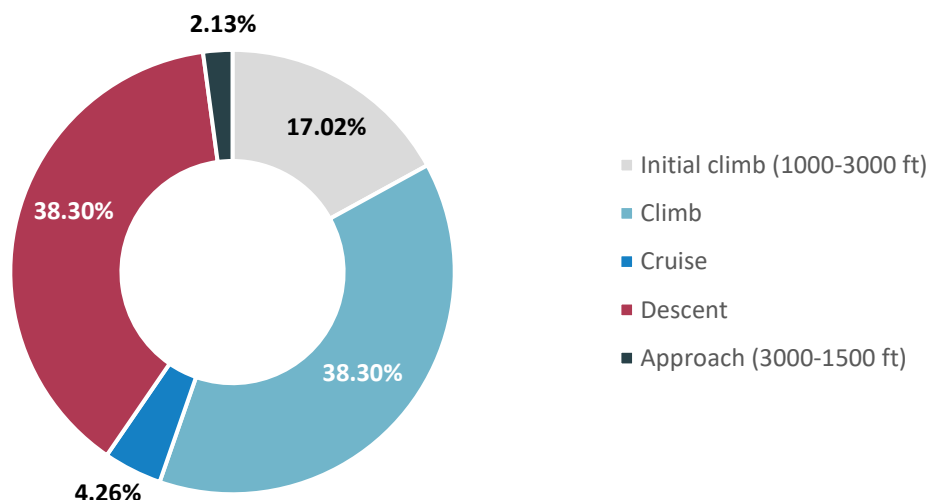


Figure 87 - Breakdown of aircraft upset by flight phase

TCAS RA – TCAS RAs were found to be the rarest operational consequence associated with turbulence encounters, with only a handful of events identified during or shortly after turbulence episodes in the recorded flight data sample. Although the normalised occurrence rate is higher for moderate than for light intensity level, the overall number of events is too small to establish a statistically meaningful relationship with aircraft response to turbulence. The results suggest that the relationship between turbulence and TCAS RA events is largely influenced by the operational context, particularly during the descent phase where both the traffic density and the turbulence occurrence rate are higher. The identified events should therefore be interpreted as occurring in temporal proximity to turbulence episodes rather than necessarily being caused by it. Further discussion of this limitation is provided in Section 7.2.

High loads – Exceedances of flight envelope protection limits are exceptionally rare and are observed exclusively during severe turbulence episodes, indicating that exceedances of these limits remain uncommon even in the most intense aircraft responses to turbulence. In contrast, exceedances of the passenger discomfort thresholds occur more frequently (0.36 events per 1,000 turbulence episodes), particularly for negative load factors below 0 g. As shown in Figure 88, these events are also slightly more frequent overall, with 165 negative-load events compared with 143 positive-load events. Furthermore, negative load exceedances persist considerably longer than positive load exceedances (see Figure 89). This indicates that weight-off-seat conditions (negative load) represent the most relevant load-related consequence from a passenger safety perspective, especially during cruise, when passengers are more likely to have their seat belts unfastened.

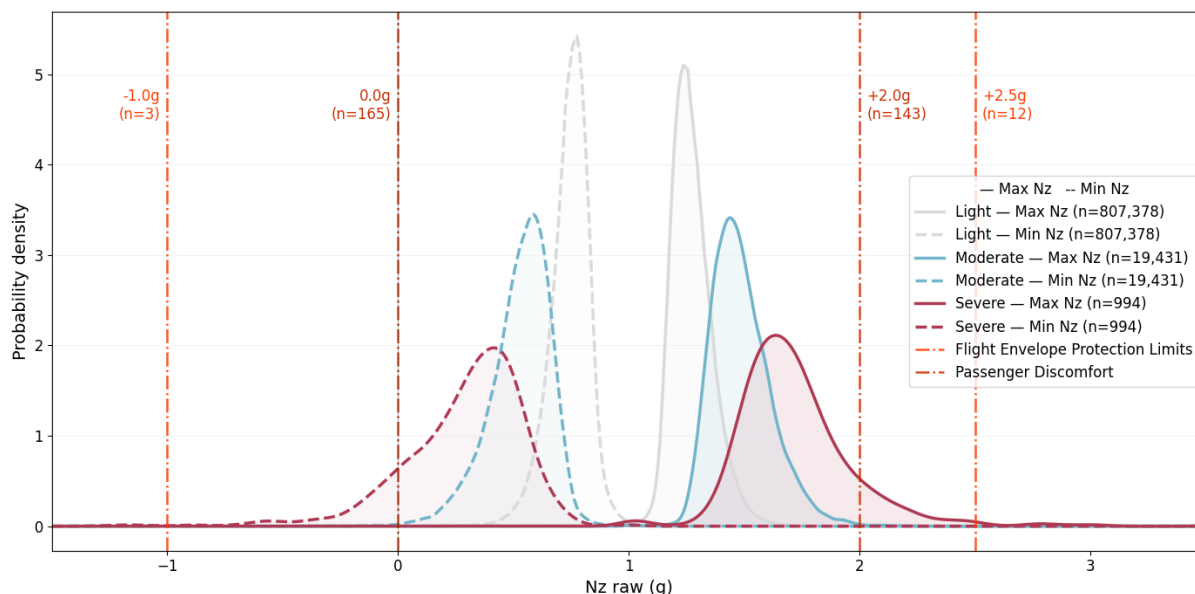


Figure 88 - Probability density of the minimum and maximum Nz value by intensity. Vertical lines show the four high load thresholds

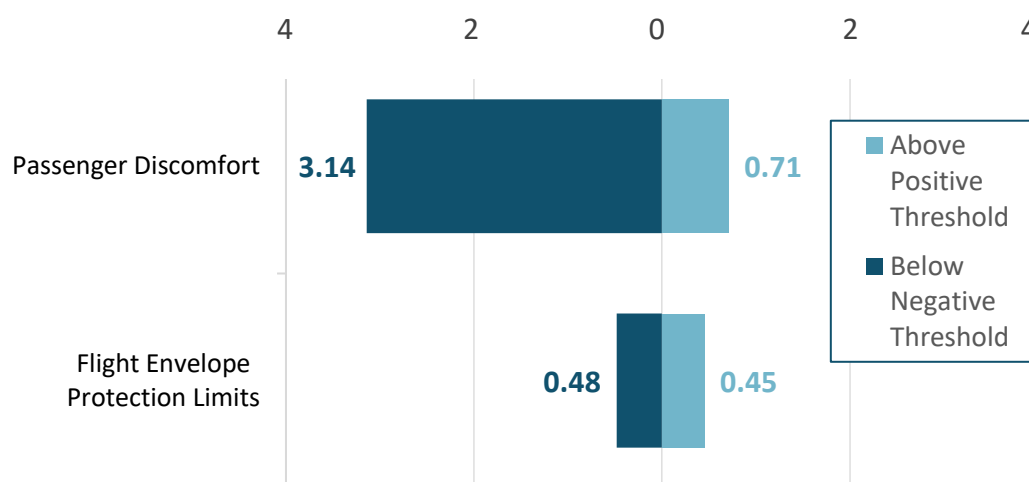


Figure 89 - Average time below (left) and above (right) the load thresholds for episodes that exceeded them at some point [s]

6.3. Analysis of safety barriers

A bow tie analysis was used to assess the performance of different types of barriers through turbulence encounters reported in the ECR dataset. The analysis complements the occurrence characterisation by focusing on the defences operating before and after an encounter, the points at which escalation was interrupted, and the consequences that remained when earlier defences were not sufficient.

6.3.1. Bow tie safety risk assessment framework and ERCS alignment

The bow tie was developed specifically for this assessment, using the ALBATROS Task 2.1 model as an initial reference and refining it with EASA's Safety Impact Assessment Task Team on Turbulence. The hazard is atmospheric turbulence in flight and the top event is a turbulence encounter that degrades the aircraft's safety margin. On the left, threats and preceding conditions are linked to preventive barriers (or defences) intended to avoid the encounter or prepare the aircraft and occupants for turbulence. On the right, recovery and mitigation barriers seek to maintain controllability, limit exposure to injuries and consequences, and recover from an unsafe state. Escalation factors may weaken or lead to failure of barriers on either side. The resulting bow tie is presented in Figure 90.

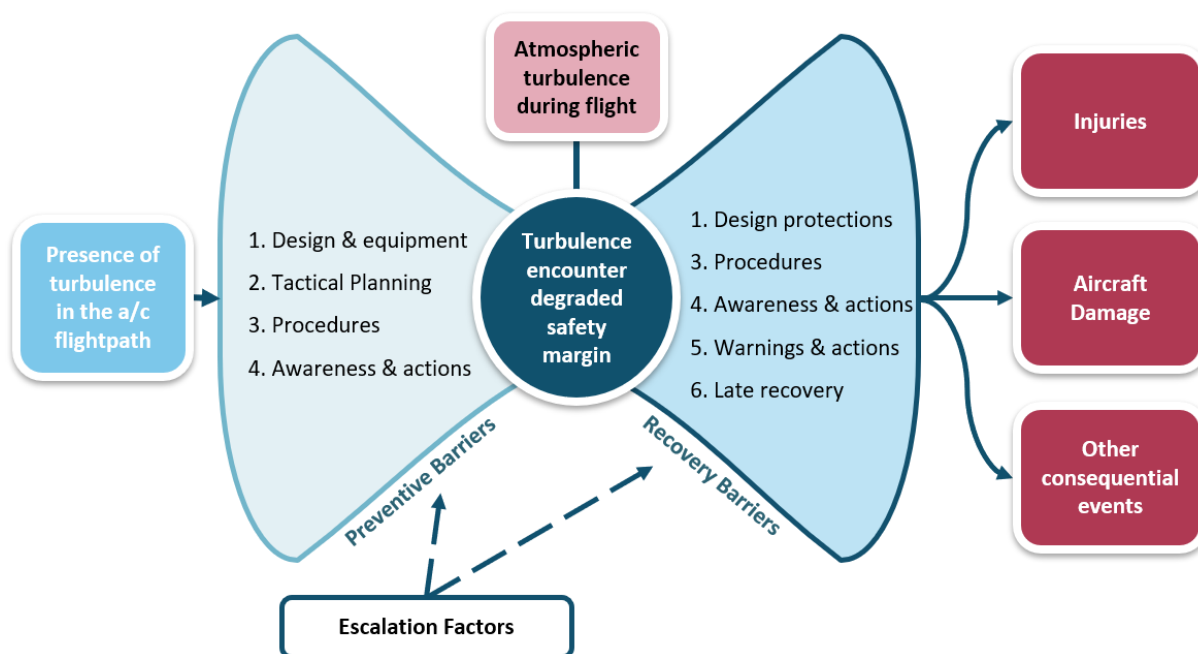


Figure 90 - Bow tie framework applied to turbulence encounters

The main bow tie components are defined in Table 14. Their position in the diagram is important: it distinguishes actions intended to prevent or prepare for the encounter from actions intended to contain or recover from it. It also shows that the reported consequential events may form part of an escalation pathway towards a potential accident outcome if the relevant barriers do not stop further progression.

Table 14 - Principal bow tie components used in the turbulence assessment

Component	Definition in the turbulence assessment
Hazard	Atmospheric turbulence during flight.
Threats or preceding conditions	Meteorological and operational circumstances that may lead the aircraft towards a turbulence encounter, including convective weather, forecasting of turbulence, changing

	weather conditions or insufficiently anticipated turbulence.
Preventive barriers	Aircraft design features, weather information, tactical planning, procedures and crew actions intended to identify, avoid or prepare for turbulence before it is encountered.
Top event	The aircraft encounters turbulence and the encounter degrades its safety margin.
Escalation factors	Conditions that may reduce barrier effectiveness, including cabin service in progress, fatigue, workload, communication problems, distraction and previous incorrect decisions or configuration errors.
Recovery barriers	Aircraft systems, warnings, procedures and crew actions that act after the onset of turbulence to maintain control, limit exposure, reduce consequences or recover from an unsafe aircraft state.
Consequential events	Safety and operational effects associated with the encounter: Injuries, aircraft damage and other events, such as overspeed, aircraft upset, level bust, diversion and any other operational effect.
Potential accident outcome	A possible high-severity endpoint to which the occurrence could escalate if the remaining barriers were ineffective. This endpoint is distinct from the reported consequential events and is not assumed to have occurred.

Consequential events and potential accident outcomes are not synonymous. For example, aircraft damage may range from minor damage to damage sufficiently severe to meet the criteria for an accident, while injuries may range from minor to fatal. The presence of a consequential event does not, by itself, establish that an accident occurred. The same type of accident may also produce outcomes of different severity.

A barrier is defined as any technical, organisational or human defence that can prevent an encounter, prepare the aircraft or occupants, contain an unsafe aircraft state, or reduce the severity of an outcome. A barrier may therefore be an aircraft design feature, weather information, a planning activity, a procedure, a crew action, a warning or a recovery measure.

The methodology for assessing barrier effectiveness was based on the barrier model defined within the European Risk Classification Scheme (ERCS) developed by EASA [36].

Under the ERCS methodology, the relevant key risk area (KRA) is the most likely type of accident to which the occurrence could have escalated. The KRA provides the reference accident type against which the remaining barriers are assessed. Aircraft upset was selected as the common reference KRA for both operational and empirical reasons. Turbulence can produce uncommanded deviations in aircraft attitude, speed, altitude and flight path which, if not contained, may escalate into loss of control. Aircraft upset is also the most frequently reported KRA in the turbulence-related ECR dataset, identified in approximately 12% of occurrences. Although the KRA is unreported in approximately 80% of occurrences, the remaining

reported KRAs are distributed relatively uniformly, with no other KRA showing the same prominence. Aircraft upset therefore provides the most relevant and consistently supported common reference for the barrier assessment, without implying that it is the applicable KRA for every individual occurrence.

The ERCS barrier model evaluates the barriers or defences remaining between an occurrence and the worst likely accident outcome associated with the selected KRA. It identifies the barrier that stopped the occurrence from escalating and assesses the barriers that remained between that stopping barrier and the potential accident outcome.

The full ERCS model contains eight barriers. The following six ERCS barrier types were analysed in this study:

1. Aircraft, equipment and infrastructure design: includes maintenance and correction, operation support, the prevention of problems related to technical factors that could lead to an accident.
2. Tactical planning: includes organisational and individual planning prior to the flight or other operational activity that supports the reduction of the causes and contributors to accidents.
3. Regulation, procedures and processes: includes effective, understandable and available regulations, procedures and processes that are complied with (with the exclusion of the use of procedures for recovery barriers).
4. Situational awareness and action: includes human vigilance for operational threats which ensures identification of operational hazards and effective action to prevent an accident.
5. Warning systems operation and action that could prevent an accident and which are fit for purpose, functioning, operational and are complied with.
6. Late recovery from a potential accident situation.

The ERCS barrier numbers constitute a logical ordering for the barrier assessment; they do not imply that the barriers always operate or fail in a fixed chronological sequence from Barrier 1 to Barrier 8. In an actual occurrence, several barriers may operate simultaneously, repeatedly or in a different temporal order. References to actions occurring before or after the top event describe their position in the bow tie, whereas references to barriers placed before or after the stopping barrier describe their position in the ERCS logical order.

Barrier 7, “Protections”, was not coded separately because it refers to occurrences whose outcomes are mitigated by intangible barriers or providence. As these factors are not directly controllable or consistently assessable, this barrier was excluded from the analysis. Barrier 8, “Low-energy occurrence”, is a special ERCS barrier for low-energy key risk areas, such as ground damage or excursions, and is not applicable to the key risk areas considered in the current assessment. The use of six groups is therefore a study-specific scoping and allocation decision, not an indication that ERCS contains only six barriers.

6.3.1.1. Barrier-action identification and narrative inference

The barrier actions were identified using inputs provided by contributors from EASA, NLR and ALG involved in the bow tie development, supplemented by relevant public safety-incident reports. These inputs were used to define potential actions for preventing, mitigating, or recovering from turbulence-related occurrences. The turbulence-related ECR narratives provided the occurrence-level evidence used to assess these candidate actions and determine their relevance to the identified safety barriers. This process identified 37 specific actions spanning technical capabilities, planning, procedures, crew monitoring and decisions, warning responses and late recovery. Each action was assigned to the ERCS barrier type whose defined safety function was the closest match and was coded as acting primarily before or after the top event. The complete action list and its ERCS barrier type association are presented in Appendix D.3.1, Table 16.

A Large Language Model (LLM), Claude Haiku 4.5, was used to analyse each turbulence-related occurrence narrative consistently, retrieve the barrier action evidenced in the narrative and assign an ERCS barrier assessment status according to the definitions in Table 15. The model was constrained to the information in the narrative and was not intended to add facts, infer an unreported physical malfunction or reconstruct actions for which no supporting evidence was available. A sample of classifications was manually validated.

Table 15 - ERCS assessment categories to classify barrier effectiveness

Status	Definition in the barrier assessment
Failed	The barrier did not prevent progression of the assessed sequence towards the potential accident outcome.
Failed assumed	No evidence was reported that the barrier failed or stopped, but it is classified as failed through the sequence-based assumption of the ERCS.
Stopped	The barrier prevented further escalation towards the potential high-severity accident outcome. This classification does not require the absence of every intermediate consequence.
Remaining	The barrier remained available between the occurrence and the potential accident outcome but was not required to stop the assessed sequence.
Not applicable	The barrier was not relevant to the circumstances or development of the occurrence.
Not reported	The occurrence narrative did not contain sufficient information to assess the barrier.

For the occurrence-level assessment, the LLM was instructed to consider the barrier actions evidenced in each narrative and retained one specific action to represent the occurrence. Where more than one barrier action was identified, the action corresponding to the last relevant barrier in the occurrence sequence was retained, based solely on the sequence supported by the narrative. The retention of one action for the occurrence-level assessment does not imply that only one barrier action was present during the actual occurrence. Several barriers may act simultaneously, and different barriers may be relevant to different consequences within the same event. Rather, the single-action representation provides a consistent basis for aggregating occurrences across the ERCS barrier framework while preserving, as far as the available narrative permits, the position of the last relevant barrier in the occurrence sequence.

6.3.1.2. *Methodological considerations*

The reliability of the assessment is dependent on the quality and completeness of the ECR narratives. Occurrence reports are generally not written with a bow tie assessment in mind. Therefore, occurrence narrative may not include information related to barriers that operated normally or may not mention any actions considered routine or successful. Consequently, absence of information about a barrier in the narrative text cannot be interpreted as evidence that the barrier was unavailable or ineffective. The level of detail also varies between reports. Some narratives provide a relatively complete sequence of events and contain information about available meteorological information, crew decisions, aircraft behaviour and consequences, while other reports only describe the principal event or outcome. These differences in the quality and content of the reports affects the ability of the model to distinguish between failed, remaining and unreported barriers.

LLM-based classification introduces additional uncertainty. Although the model was constrained to the narrative information and a sample was manually validated, classifications may remain sensitive to wording, incomplete descriptions and ambiguous event sequences. Finally, the use of a common reference key risk area (aircraft upset) improves comparability across the dataset but simplifies the occurrence-specific barrier assessment, as the most applicable KRA to each occurrence may differ according to how each occurrence developed. Similarly, retaining only the action associated with the stopping barrier means that the assessment records the principal barrier that prevented further escalation, rather than every barrier that may have contributed to the occurrence. Other barriers may have acted simultaneously or sequentially, and different barriers may have limited different consequences within the same occurrence.

Future work could therefore perform separate assessments for each consequence pathway identified. The applicable KRA and potential accident outcome could then be determined by each pathway followed by separate sequences of barriers developed for injuries, overspeed, level bust, damage and other relevant outcomes.

6.3.2. Barrier assessment results

The barrier assessment results, aggregated by the ERCS barrier types, are presented in Figure 91. The figure describes how each barrier type was classified within the reported ECR occurrence narratives; the percentages are not estimates of operational barrier reliability or effectiveness across all flights or turbulence encounters. The results indicate that different barrier types can contribute to preventing or containing escalation, rather than that a single barrier type prevents an accident.

Aircraft design and tactical planning are predominantly classified as Failed or Failed assumed. However, these results are strongly influenced by the construction of the dataset, which contains reported turbulence encounters but does not contain encounters that were successfully avoided and therefore generated no occurrence report. Their results are retained in the figure to present the complete classification output and

to make this selection effect visible, but they cannot be used to assess the general effectiveness of these two barrier types.

For the remaining barrier types, Stopped indicates that the barrier was classified as the final evidenced barrier preventing further progression towards the common high-severity accident outcome defined in Section 6.3.1. It does not mean that the barrier prevented the turbulence encounter itself or that every intermediate consequential event was avoided.

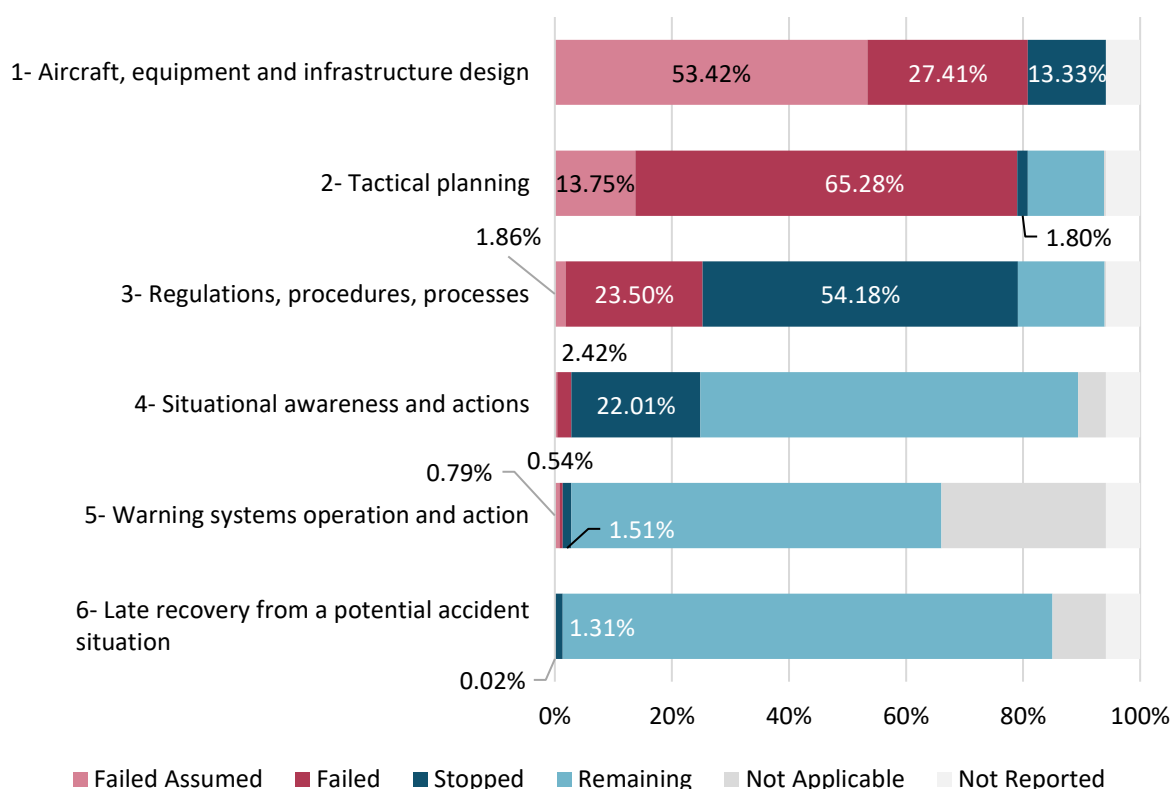


Figure 91 - Aggregated assessment of the ERCS Barrier types in the turbulence-related ECR occurrences

The six ERCS barrier types can be considered as three broad layers of defence: prevention and preparation, mitigation of the developing occurrence, and late recovery. These groups should not be interpreted as a fixed chronological sequence in which barriers necessarily operate or fail according to their ERCS number. Barrier actions may interact, operate simultaneously, or contribute both before and after the turbulence encounter.

The design barrier, covering the aircraft, its equipment and supporting infrastructure, is recorded as failed in a large share of occurrences. This reflects the construction of the dataset, which by definition prevents encounters that were not avoided. Instances in which aircraft design contributed to the successful detection and avoidance of turbulence -for example, through weather radar performance- or in which airframe

structural integrity and cabin interior damage resistance enabled the aircraft to withstand a turbulence encounter without damage or consequences are generally not reported. Therefore, the ECR data sample is not representative to assess the effectiveness of this barrier. The design barrier can also act after the encounter: structural strength and flight-envelope protections are intended primarily to limit the severity of aircraft-state consequences and prevent progression towards structural failure or loss of control.

Tactical planning, the pre-flight and dispatch measures aim to (re-)route the flight around areas of turbulence or anticipate turbulence. Its high proportion of failed classifications is affected by the same selection effect: the dataset contains encounters that were not fully avoided at the planning stage and does not contain occurrence reports for flights that successfully avoided turbulence.

Procedures are the most frequently observed stopping barrier, preventing further progression towards high-severity outcomes in about half of the assessed turbulence-related occurrences. This barrier contains actions both before and after the encounter. Before the encounter, cabin preparation, seatbelt use, suspension of service and turbulence-penetration procedures can reduce occupant exposure to injuries or prepare the aircraft and its occupants. During or after the encounter, operational procedures can help contain aircraft-state deviations, support recovery and reduce the severity of the resulting consequences.

Situational awareness and crew action are also frequently identified as the stopping barrier. Crew vigilance, interpretation of weather information and timely operational decisions may reduce the likelihood or duration of an encounter, while monitoring and corrective actions after the onset of turbulence may contain aircraft-state deviations and limit further escalation. These results indicate that crew vigilance and corrective action reinforce rather than replace the procedural barrier.

Warning systems generally remain available as barrier rather than acting as the decisive stopping barrier. A warning cannot prevent the condition that triggers it, since the exceedance is what activates the alert. Its role is to prompt corrective action by the flight crew before that condition escalates towards structural damage or a loss of control. In that respect, the warnings systems barrier mitigates the severity of outcomes or consequences of occurrences.

Late recovery is the final barrier and is rarely called upon based on the analysed data sample. In most occurrences this barrier remains available but is not required, since the event has already been mitigated at the procedural or situational awareness barrier. This barrier preserves an additional safety margin in case the event further escalates.

A detailed assessment of the actions associated with each barrier type is presented in Appendix D.3.2, together with their relationship to the reported consequential events. The appendix shows descriptive links between the barrier action reported in an occurrence, its assessed status and the consequential events recorded in the same occurrence, identify recurring co-occurrence patterns.

The overall results of the detailed assessment show that different consequences follow distinct pathways and are controlled by different barriers. Aircraft state related events, such as overspeed, aircraft upset and level bust, are primarily contained by structural and flight envelope protections, crew monitoring and warning system responses. Injuries follow a separate cabin-exposure pathway in which the use of restraints and timely crew action to secure the cabin and suspend cabin service reduce occupants' exposure to turbulence consequences and limit the likelihood or severity of injury. Aircraft flight envelope protections may therefore operate successfully as barrier even if an injury occurs. Where aircraft damage was reported, it was generally minor, which is consistent with structural tolerance limiting further escalation. Operational consequences, such as diversions, may similarly represent successful risk reduction decisions rather than indicate barrier failures.

Because the dataset comprises reported turbulence encounters, the preventive barriers intended to avoid the encounter have not, in these cases, prevented it. Once turbulence was encountered, mitigation and recovery barriers could maintain aircraft control, reduce the likelihood or severity of injuries and damage, and stop further escalation towards the reference potential accident outcome. The occurrence of a reported consequence does not, by itself, indicate barrier failure, because a barrier may have limited its severity or prevented a more serious outcome. Overall, the occurrences demonstrate a layered defence is in place: procedures and crew actions most frequently avoid further escalation, while design protections, warning systems and late recovery provide additional mitigation to avoid consequences or accident outcomes.

6.3.3. Escalation factors

Escalation factors were derived from the Event Type enhanced attribute (seen in Section 4.1.6), as the consequential events. For this analysis, Event Type values describing conditions that could increase the likelihood of turbulence encounters or reduce barrier effectiveness were classified as escalation factors, while values describing the effects of the encounter were classified as consequential events. The factors may occur together and should be interpreted as contextual conditions reported in the narrative, rather than as evidence that they caused the encounter or its consequences. Figure 92 presents the escalation factors identified before or during the turbulence encounters.

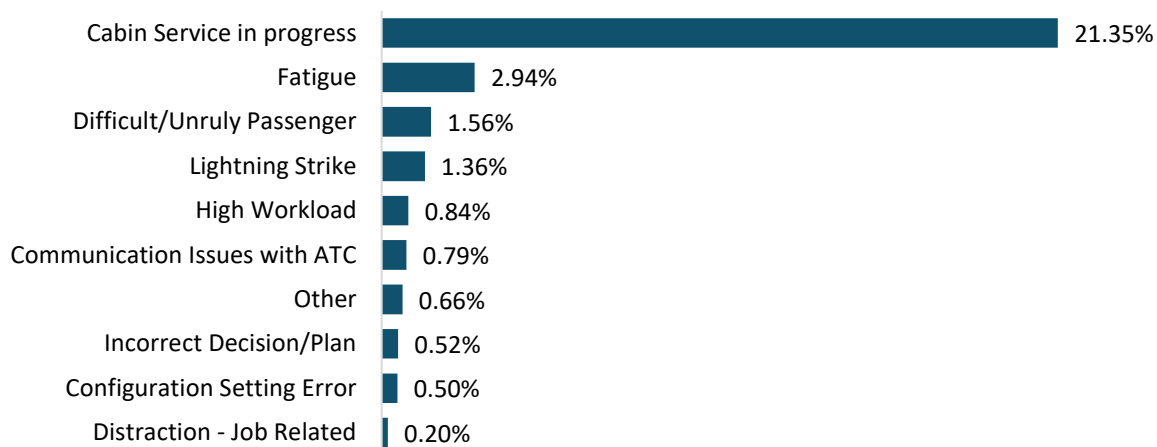


Figure 92 - Escalation factors identified in the turbulence-related ECR occurrences

Cabin service in progress was by far the most frequently reported escalation factor, occurring in approximately one fifth of the occurrences. This finding is consistent with the injury characterisation presented in Section 5.4. During cabin service, cabin crew may be standing or moving through the cabin or galleys, passengers may be out of their seats, and trolleys or other service equipment may not yet be secured. These conditions increase the likelihood of injury when turbulence occurs and increase the time required to discontinue service, secure equipment and allow cabin crew and passengers to become seated and restrained.

Escalation factors may affect several ERCS barrier types simultaneously. The relationships below describe how the reported escalation factors could influence the barrier sequence; they do not demonstrate causality or quantify the effectiveness of individual barriers.

- Cabin service in progress primarily affects barrier 3 “Regulations, procedures and processes” and barrier 4 “Situational awareness and action”, regarding those actions associated with cabin crew responsibilities. It increases occupant exposure to injuries and increases the time required for cabin crew to discontinue service, secure the cabin, conduct the required cabin safety checks and take their seats and fasten their restraints.
- Fatigue, high workload or job-related distraction may affect barrier 4 “Situational awareness and action”, barrier 5 “Warning systems operation and action” (recognition of and response to warnings), and barrier 6 “Late recovery”. Reduced alertness, time pressure or attention directed to other tasks can impair weather information interpretation, decision-making, monitoring, communication and the timely execution of corrective actions.
- Difficult or unruly passengers primarily affects barrier 3 “Regulations, procedures and processes” and barrier 4 “Situational awareness and action”. They may distract cabin crew, increase workload and delay passenger restraint or cabin securing.
- ATC communication issues may affect barrier 2 “Tactical planning”, barrier 3 “Regulations, procedures and processes” and the barrier 4 “Situational awareness and action”, by delaying the

exchange of turbulence information, facilitating route or flight level changes, and coordination of avoidance or recovery actions.

- Incorrect decisions or plans and configuration setting errors primarily affects barrier 3 “Regulations, procedures and processes”, barrier 4 “Situational awareness and action”, barrier 5 “Warning systems operation and action”. An unfavourable route, flight level or operational decision may reduce turbulence avoidance opportunities, delay cabin preparation for turbulence, or increase reliance on recovery barriers.
- Lightning-related events may place additional demands on Barrier 1 “Aircraft and equipment design”, barrier 3 “Regulations, procedures and processes” and barrier 4 “Situational awareness and action” by increasing flight crew workload and distraction, and barrier 5 “Warning systems operation and action” (recognition of and response to warnings).

Overall, the escalation factors show how operational and human performance conditions can weaken available defences or increase likelihood of turbulence encounters and potential consequences. Cabin service is particularly relevant to the likelihood of injury, while fatigue, workload, communication difficulties, distraction and decision or aircraft configuration errors can affect several aircraft- and crew-related barriers across the bow tie.

7 DISCUSSION OF RESULTS

7.1. Summary of main findings

The principal findings presented in the study are summarised below.

General characterisation and turbulence observation frequency

The recorded flight data provide a measure of physical observation to turbulence. Turbulence affects approximately 18% of flights, most of which encounter a single turbulence episode comprising between two and three isolated turbulent events, with an average episode duration of the order of one minute and an average excursion of the load factor signal of approximately 0.5 g. This physical observation frequency is overwhelmingly dominated by light intensity episodes (RMS-g between 0.1 and 0.2), which accounts for more than 97% of episodes, while severe intensity is rare, at approximately one episode in every thousand (0.1%).

The ECR data sample is, by construction, composed of turbulence encounters that pose a significant enough safety risk to warrant reporting to the ECR. This effectively translates into a bias towards events with outcomes and consequences, which in turn is generally associated with higher reported turbulence intensity. In the ECR data sample, approximately half of the turbulence-related occurrences are of moderate or severe intensity, while the other half are of light or unreported intensity. The recorded flight data, on the other hand, is assumed to provide an unbiased measure of physical exposure to turbulence. Direct comparisons between the two datasets should therefore be made bearing in mind this key difference and

the distinct meaning of intensity in each. In the recorded flight data, the intensity of a turbulence episode is defined according to the predefined thresholds on the RMS of the N_z signal introduced in Chapter 4, applied consistently across the entire volume of recorded flight data. In the ECR dataset, by contrast, intensity refers to the intensity reported by the stakeholder submitting the occurrence. It is therefore qualitative, subjective, and often strongly affected by the presence of consequences, for two reasons. First, because events of higher physical intensity, that is, a higher objective magnitude of the aircraft response as measured in the recorded flight data, are more likely to cause the outcomes or consequences that warrant reporting to the ECR. And second, because the presence of such consequences is itself likely to bias the reporter towards a subjective perception of higher intensity.

Nevertheless, despite these differences in the meaning of intensity, an interesting phenomenon is observed when comparing the exposure to turbulence at different intensity levels across the two datasets. On aggregate the two datasets differ significantly, due to the fundamentally different ways in which they measure intensity: the recorded flight data is dominated by light turbulence (with moderate around 2% of episodes and severe at 0.1%), whereas roughly half of the turbulence-related ECR occurrences are moderate or severe, a direct reflection of the reporting bias rather than of the physical frequency of encounters.

Interestingly, the gap between the two datasets narrows as intensity increases. Light-intensity exposure rates differ by about four orders of magnitude, moderate exposure rates by one to two, and severe exposure rates converge to within roughly one order of magnitude (0.24 per 1,000 flights in the recorded flight data against 0.05 to 0.09 in the ECR). This apparent convergence should not, however, be interpreted as evidence of a direct relationship between the two intensity scales, which are defined in fundamentally different ways and cannot be matched on an event-by-event basis.

Rather, the observed behaviour is consistent with the nature of the ECR itself. The ECR is inherently biased towards encounters that result in consequences warranting reporting, such as injuries, aircraft damage or other effects relevant to aviation safety. Physical turbulence intensity is, in turn, a key determinant of the likelihood and magnitude of such consequences. Consequently, as physical intensity increases, a greater proportion of encounters would be expected to result in reportable consequences, causing the distribution of reported occurrences to increasingly reflect the distribution of physical exposure (the correlation between physical intensity and consequential events is corroborated by the analysis of consequential events in the recorded flight data, see Section 6.2). This effect is reinforced by the biases described above: encounters of lower physical intensity may be reported as moderate or severe, and different stakeholders may assign different reported intensities to encounters of similar physical intensity. The relative contribution of these effects cannot be isolated from the available data.

The narrowing of the gap at higher intensity should therefore be understood as a consequence of the reporting process rather than as evidence that the two intensity scales become equivalent. At lower physical intensities, where encounters are less likely to produce consequences that trigger reporting, the ECR

provides a highly incomplete and behaviour-dependent representation of physical exposure. As physical severity increases, the consequence-driven nature of reporting means that the ECR can be expected to follow the overall behaviour of the physical exposure distribution more closely. The apparent correlation is therefore expected to become more pronounced towards the severe end of the intensity spectrum, while the correspondence between an individual reported intensity and a physical intensity remains uncertain.

Against this background, severe turbulence is the regime in which the two independent datasets provide their closest agreement in terms of order of magnitude. Subject to the biases already noted, the data available for this study place the two exposures at a ratio of between two and four turbulence-related occurrences in the ECR for every ten severe episodes in the recorded flight data. This ratio should *not* be interpreted as a capture rate, or as indicating that 20 to 40% of severe turbulence episodes are reported to the ECR. The two intensity scales do not correspond on an event-by-event basis, and encounters of lower physical intensity may be reported as moderate or severe because of the aforementioned biases.

Nor would an exact numerical match between the two datasets be expected even if the intensity definitions were perfectly aligned. Under Regulation (EU) No 376/2014, mandatory reporting applies to events that may represent a significant risk to aviation safety, rather than to every occurrence of a particular physical intensity. Consequently, not every severe turbulence encounter will necessarily give rise to a reportable event.

The ratio should therefore be regarded only as an indicative measure of the relative magnitude of the two quantities in the datasets available, and not as an estimate of the rate at which severe turbulence is reported to the ECR. More broadly, the key finding is *not* that the two intensity scales become interchangeable at higher severity, but that the consequence-driven reporting bias inherent in the ECR means that its overall behaviour is expected to resemble that of physical turbulence exposure more closely as the intensity of encounters increases.

A shift in reporting practice is also evident in the ECR data. The frequency of turbulence-related occurrences in the ECR data sample rose sharply in 2023, in contrast with the steady rise in overall ECR reporting across the study period. This step is attributed to a change in reporting practices rather than the result of an increase in the prevalence of turbulence. This change is likely the result of two coinciding developments. The first is the entry into force of the ERCS risk-scoring requirement in January 2023 under Regulation (EU) 2021/2082, which made the reporting of lower severity encounters more likely. The second development is the growing recognition of turbulence as a safety concern. The ICAO annual safety report of 2024 identified turbulence as the leading cause of accidents in 2023, and industry initiatives such as IATA's Turbulence Aware platform, aimed at improving turbulence monitoring and mitigation, have expanded over recent years with the addition of new airlines and data integrators. The "additional" turbulence-related occurrences captured in the ECR appear to be predominantly lower-severity encounters. This is primarily

indicated by the increase in the “Not Reported” category for turbulence intensity, suggesting that many of these occurrences may previously have gone unreported.

The recorded flight data allows the physical structure of a turbulence episode to be examined in a way the ECR data sample cannot, because the former is an objective, numerical measurement of the encounter, available consistently for every episode. The ECR, by contrast, is limited to what is subjectively reported by the stakeholder, which tends to focus on the outcome of the occurrence; physical properties such as episode duration are generally not reported at all. The recorded flight data shows that episode duration increases with intensity, while the oscillatory frequency of the turbulence-induced aircraft response, as measured through the vertical accelerometer signal, remains essentially constant. More severe turbulence is therefore characterised principally by longer episodes with larger load factor excursions, rather than by more rapid oscillations induced on the airframe. Once the intensity level is accounted for, the average episode duration and the associated load factor excursions appear to be constant across flight phases.

Turbulence by flight phase and altitude

Turbulence episodes are strongly skewed towards the lower altitude bands, occurring primarily at lower altitudes and particularly towards the end of the flight: approximately 70% of episodes take place during descent and approach. The skew is especially striking once the data is normalised by the average duration of each flight phase. Cruise is the longest phase in the dataset but has the lowest rate of turbulence episodes per minute of flight time; instead, we observe a higher rate of turbulence episodes towards the lower altitude bands and end-of-flight phases. This finding is attributed to three factors. The first is the greater observed turbulence frequency, at lower altitudes, to meteorological and terrain-induced phenomena. Several turbulence-generation mechanisms are confined to the lower troposphere because they arise from the atmosphere's coupling to the Earth's surface, including mechanically induced turbulence, produced by terrain through friction and flow separation, and thermally induced turbulence, produced by convective thermals and by wind shear associated with temperature inversions. The second factor is the way in which the magnitude of the aircraft's response to turbulence changes over the course of a flight. The higher air density at lower altitudes and the lower wing loading towards the end of a flight, as aircraft weight reduces, both amplify the aircraft response to a given atmospheric disturbance. The third factor is the greater operational flexibility available in cruise. During cruise, the flight crew can generally deviate in altitude or heading to avoid areas of known turbulence. On the other hand, during climb, descent and approach, arrival or departure operational procedures and other nearby air traffic may limit the opportunity to avoid areas of turbulence. Such deviations carry an operational cost and are not always possible, but the option exists and may be prioritised over other considerations, particularly when the forecasted or experienced turbulence is severe.

The recorded flight data and the ECR data sample provide markedly different pictures in terms of the distribution of turbulence encounters by flight phase. In the turbulence-related occurrences from the ECR, cruise flight is accounting for almost half of all turbulence-related occurrences (approximately 45%), with

the other flight accounting for a much smaller proportion. This dominance of the cruise phase, and its stark contrast with the flight phase distribution of episodes measured in the recorded flight data (approximately 9%), is noteworthy. The difference is attributed to the combination of three factors. The first is the difference in the average duration of the cruise phase covered by the two datasets. The ECR data contains proportionally more long-haul operations than the recorded flight data set and, therefore, reported occurrences are associated on average with longer cruise phases. The second explanation is the predominance of clear-air turbulence (CAT) in cruise. Since CAT cannot be detected by conventional on-board weather radar, its lower predictability leaves crews less time to react and to prepare the cabin in anticipation of turbulence. The third factor is the level of cabin activity, which is greatest during cruise, when cabin service may be in progress and passengers may not have their seatbelts fastened and moving around in the cabin. The concentration of CAT at cruising altitudes, the greater cabin activity during cruise, the reporting bias of the ECR towards higher-severity encounters, and the longer average cruise duration arising from the larger share of long-haul operations in the ECR data set explain why the cruise phase produces the largest share of turbulence-related reports to the ECR.

Turbulence near top of descent

A further insight can be gained by analysing the specific locations within each flight phase where turbulence episodes occur in the recorded flight data. A peak in the distribution of episodes is observed towards the end of the cruise, close to the top of descent. A possible explanation for this late-cruise peak relates to differences in weather radar technology, in combination with related factors such as crew proficiency in radar adjustment, attention and mental models, and the workload associated with the transition from cruise to descent. Aircraft equipped with older-generation weather radars generally require active crew management of antenna tilt and gain and may offer less effective detection and depiction of convective weather, whereas modern multiscan radars can manage these parameters automatically and incorporate temperature-based gain adjustment. This hypothesis was tested by separating the analysis into two aircraft fleet groups. One group represented an older-generation fleet, assumed to carry older radar technology that requires manual tilt and gain operation, and a second group of a newer generation aircraft, typically equipped with weather radars with automatic tilt management, more advanced gain management and weather analysis capabilities. With a sufficient sample size in both groups, the peak at the end of cruise disappears for the newer generation aircraft, which suggests that aircraft generation, used here as a proxy for weather radar technology, is a relevant factor and a plausible contributor to the peak. This analysis underlines the effect of weather radar capabilities on turbulence encounters near top of descent, highlighting the importance of managing potential encounters during this part of the flight carefully, particularly in older generation aircraft.

Turbulence-related injuries and damage

Injuries are reported in approximately 15% of turbulence-related ECR occurrences. Given the reporting bias of the ECR data sample towards higher-severity events, this figure should not be interpreted as implying that 15% of all turbulence encounters result in injury. Injuries are concentrated in occurrences of moderate

and severe intensity, although this association is partly an effect of the reporting bias since occurrences involving injuries are more likely to be reported. Among the injured, there is a disproportionately high number of cabin crew, followed by passengers, whilst pilots are injured far less frequently. Cabin crew injuries due to turbulence are typically associated with performing cabin service at the time of injury and generally occurring in the galley. Passengers are at least three times more likely to be injured when seated without a fastened seatbelt compared to when wearing a seatbelt. Moreover, the injuries sustained by passengers not wearing a seatbelt are also more likely to be serious. Aircraft damage is considerably less common than injury, and reported in only about 5% of occurrences. Damage is likewise associated with higher intensity levels, although the data are affected by the same reporting bias as for injuries.

Type of turbulence

Information on the type of turbulence is only available in the ECR data sample. Convective turbulence is approximately two and a half times more prevalent than clear-air turbulence (CAT), a proportion that remains constant across the study period from 2019 to 2025. CAT is associated with a higher likelihood of injury. Approximately 20% of CAT occurrences involve a reported injury, compared to less than 10% of convective turbulence occurrences, with the overall rate across all occurrences being 15%. The severity level of the injuries due to turbulence is comparable between the two types of turbulence. CAT is therefore associated with a higher frequency of injuries, but not with more severe ones.

The higher proportion of injuries in CAT occurrences, and its association with higher intensity occurrences, does not necessarily reflect an inherent property of this turbulence type but rather how and when it is encountered. As noted above, CAT is more difficult to anticipate because it cannot be observed on the on-board weather radar, which reduces the possibility and available time for detection and preparing for turbulence. At the same time, CAT is also most prevalent in cruise, where the combination of increased cabin activity and lower seatbelt usage increases the likelihood of injuries occurring when turbulence is encountered. This explains the higher likelihood of injury in clear-air turbulence encounters, which in turn also explains its association with higher intensity levels.

These findings are particularly relevant in the context of climate change. Clear-air turbulence is the turbulence type for which the relationship with anthropogenic warming is most consistently established, with observations already showing changes in the atmospheric conditions associated with CAT and future projections indicating a substantial increase in severe CAT frequency [25]. Convective turbulence is also expected to intensify in a warmer and moister atmosphere, although projections are subject to greater uncertainty [27]. Because CAT is both associated with a higher likelihood of injury and more difficult to anticipate, an increase in CAT exposure could compound the safety concern identified in this study. The results therefore reinforce the importance of improving CAT detection and forecasting and of providing timely turbulence information, while continued advances in onboard weather-radar technology remain important for the management of convective turbulence.

The turbulence exposure characterised in this study also provides a baseline against which these future changes can be monitored. Repeating the analysis as additional data become available would allow changes in turbulence exposure, intensity and associated consequences to be assessed alongside changes in weather patterns, aircraft technology and operational practices.

Short-haul versus long-haul

The distinction between short-haul and long-haul operations is only available in the ECR dataset, as the recorded flight data cannot be presented by route due to the Data Governance constraints. Approximately 65% of turbulence-related ECR occurrences are associated with short-haul operations and 30% with long-haul; the remaining 5% have not reported a route type. Long-haul operations are associated with a higher proportion of CAT and represent higher intensity occurrences, most likely a reflection of their longer cruise phase. The likelihood of injury is nonetheless similar for both route types. In conclusion, the route type has no observed effect on injury likelihood and severity.

Geographical distribution

The geographical distribution of turbulence-related occurrences in the ECR data sample is examined through the frequency with which turbulence is reported in each state, relative to that state's overall reporting to the ECR. Clear-air turbulence occurrences seem to be concentrated near Iceland and the North Atlantic, whereas convective weather turbulence is most prominent over Southern Europe and the Mediterranean. The recorded flight data are constrained by Data Governance rules as to what can be presented in the report about geographical distribution. Keeping these constraints in mind, the available data suggest that moderate and severe turbulence episodes in cruise most often occur in the vicinity of the mountainous regions of the Alps and the Pyrenees.

Turbulence seasonality

In the turbulence-related occurrences from the ECR, the turbulence frequency per 1,000 flights shows a seasonality profile with a winter peak and a secondary summer peak that is particularly evident in occurrences involving injuries. When the data are split by intensity levels, the rate of light turbulence is approximately flat across the year, showing no clear seasonality. This is likely due to the small sample size, since turbulence of light intensity is generally unlikely to be reported to the ECR. Moderate and severe turbulence occurrences, by contrast, follow a pattern with a winter peak and a smaller secondary peak in summer. The aggregate is thus determined by the moderate and severe samples. At an aggregate level, the seasonality of the turbulence episodes detected in the recorded flight data appear to differ from the seasonality of the ECR occurrences. However, this is a consequence of the fact that the flight data are dominated by light episodes, while the ECR occurrences are biased towards higher intensity events. If we consider only severe intensity episodes a seasonal trend becomes apparent, which is broadly comparable to the seasonality in the severe turbulence occurrences from the ECR. This mirrors the pattern observed for the overall turbulence observation frequency.

Turbulence and consequential events

In addition to the characterisation of turbulence encounters, the study also examined the consequential events potentially caused by turbulence. With regard to the ECR data sample, the analysis is based on the enhancement of the Event Type attribute carried out during the data-quality phase of the processing. It combined the Event Type information already present in the structured ECCAIRS2 data with information extracted from the occurrence narratives. The enhanced Event Type attribute was consolidated into a set of consequential event categories. Overspeed is the most frequently reported consequence, occurring in about a quarter of turbulence-related occurrences, followed by injuries to persons on board, aircraft upset, and operational consequences such as diversions. Aircraft damage and loss of separation are the least frequently reported consequential events.

With regards to the recorded flight data, the analysis of the consequential events is dependent on the available flight parameters in the recorded flight data and the feasibility of identifying a particular event based on these parameters. The potential consequential events were reviewed, and a subset was selected for analysis based on what could be computed from the flight data. The results show that consequential events are generally associated with higher intensity episodes, with the frequency rising by approximately one to two orders of magnitude per 1,000 flights relative to light turbulence. Autopilot disengagement is the most common consequential event, at a frequency of the order of ten to one hundred events per 1,000 episodes. Notably, over 25% of these events involve repeated disengagements (as opposed to a single one), indicating that the autopilot did not cope well with turbulence in one quarter of turbulence episodes. This finding warrants closer examination of the autopilot's ability to remain engaged during turbulence, and its ability to surpass the turbulence when re-engaged. High load events are common in severe intensity episodes, which by definition involve larger load excursions, with exposure rates in the order of 10 to 100 events per 1,000 episodes of severity intensity. Most high load events fall within the range in which passenger discomfort may occur, with negative-load events below 0 g (which may give rise to weight-off-seat conditions) being particularly common, affecting 10% of severe intensity episodes (exposure of 100 events per 1,000 severe intensity episodes). Exceedances of the flight-envelope protection limits are rare, with an exposure of 10 events per 1,000 severe intensity episodes. Overspeed events and aircraft upsets occur at similar rates, ranging from between 0.1 and 1 event per 1,000 episodes of light intensity to around ten events per 1,000 episodes of high intensity. The former generally take the form of Mach number (Mmo) exceedances during cruise, and the latter are most often caused by positive pitch-angle exceedances.

Finally, the ECR data were used to assess how safety barriers contributed to avoiding, preparing for, mitigating and recovering from reported turbulence encounters. The analysis used a bow tie framework in which a turbulence encounter that degrades safety margins is treated as the top event. Preventive and preparatory barriers act before the top event, while mitigation and recovery barriers act during or after the encounter to limit its effect and prevent further escalation. Reported consequential events, including injuries, aircraft damage, overspeed, aircraft upset and level bust, are possible effects of the encounter and do not necessarily constitute accidents. The assessment used aircraft upset as the common reference ERCS

key risk area and considered escalation towards its potential high-severity accident outcome. It was an ERCS-aligned comparison of barrier performance rather than a complete ERCS risk assessment of each occurrence.

Six of the eight barriers in the ERCS model were analysed, grouped functionally into prevention and preparation, mitigation, and late recovery. The first layer, prevention and preparation, is recorded as having failed in a large share of occurrences. This is a direct consequence of the composition of the ERC dataset, which generally contains occurrences in which turbulence was encountered and produced consequences serious enough to warrant reporting to the ECR, while encounters that were successfully avoided are usually not included. In the reported occurrences, procedures and crew actions were most frequently identified as stopping further escalation, while situational awareness, flight-envelope protections, warning systems and late-recovery measures provided additional mitigation or remained available as further safety margins. The results therefore indicate a layered barrier structure in which several barriers may contribute, rather than a single barrier being responsible for preventing every consequence.

The clearest distinction concerns the barrier-action patterns associated with different types of consequence. Aircraft-state events, such as overspeed, aircraft upset and level bust, were associated mainly with structural and flight-envelope protections, crew monitoring and warning-system responses. Injuries followed a cabin-exposure pattern in which the use of restraints and timely crew actions to secure the cabin and suspend cabin service reduced occupants' exposure to injuries and limited the likelihood or severity of injury. Consequently, aircraft flight-envelope protections may operate successfully even when a cabin injury occurs, because these barriers address different escalation mechanisms. Reported aircraft damage was generally minor, which is consistent with structural tolerance limiting further escalation, while operational consequences such as diversions may represent appropriate risk-reduction decisions rather than barrier failures. When these findings are considered together with the characterization analysis, which shows greater difficulty in anticipating clear-air turbulence and increased cabin exposure to injuries during cruise, the main area for improvement is earlier and more reliable turbulence information combined with timely restraint use, cabin securing and suspension of service, particularly before higher-intensity encounters. At the same time, the existing design, warning and recovery barriers should be maintained because they provide important protection against escalation of aircraft-state events.

7.2. Limitations

The limitations described below define the boundaries within which the results should be interpreted. They do not affect all findings equally. The large volume of recorded flight data and the complementary information contained in the ECR support the identification of robust aggregate patterns within the analysed datasets. The greatest uncertainty concerns extrapolation beyond those datasets, causal interpretation, direct comparison between the two data sources and estimation of barrier reliability. The impact of each limitation on the results and conclusions is therefore explained below.

7.2.1. Turbulence-related ECR occurrences

Reporting bias towards higher severity level occurrences – The ECR represents reported occurrences rather than the complete population of turbulence encounters. Encounters involving injuries, aircraft effects or operational disruption are more likely to be reported than encounters managed without consequences. This has a substantial impact on absolute proportions: for example, the reported shares of occurrences involving injuries, damage or other consequential events must not be interpreted as the probability of those consequences across all turbulence encounters. Similarly, ECR metrics normalised per flight describe the frequency of reported turbulence occurrences, rather than the physical frequency of turbulence exposure. Relative patterns within the reported dataset remain informative, but associations with severity may be amplified because the consequences themselves influence whether an occurrence is reported.

Subjective assessment present in ECR occurrence reports – ECR reports reflect the information available to, and the judgement of, the reporter. Turbulence intensity and, to a lesser extent, turbulence type may be influenced by the aircraft response and the consequences experienced. This introduces classification uncertainty and may partly strengthen observed relationships between reported intensity and injuries or damage. The ECR intensity categories therefore describe perceived or reported intensity and cannot be directly equated with the RMSg-based aircraft-response categories derived from recorded flight data.

Incomplete taxonomy fields and narrative information – Several attributes contain a large proportion of “Not Reported” values, particularly turbulence type, intensity and aircraft damage. Missing information is unlikely to be random: routine circumstances and successful actions may be less likely to be recorded than unusual or consequential ones. A missing value therefore cannot generally be interpreted as evidence that the corresponding factor was absent. For instance, if damage was not reported, it has been assumed that there was no significant damage in the event. This assumption is a limitation obviously, as the absence of a data value is not the same as absence of the factor. An important consideration is the availability of turbulence-type information. Although the field is not recorded in approximately three quarters of the occurrences, the remaining classified occurrences provide a valuable basis for characterising the types of turbulence reported in the dataset. Consequently, turbulence-type metrics were calculated for the classified subset and is considered representative for the reported occurrences as the subset sample size is still sufficiently large.

Uncertainty associated with automated classification and enrichment – The manual review of 200 candidate occurrences produced 99% agreement for the classification of turbulence versus non-turbulence, providing confidence in the identification process. However, this validation does not quantify the accuracy of every attribute subsequently extracted or enhanced by the LLM, such as turbulence type, Event Type, injury activity or injury location. These classifications remain sensitive to narrative completeness, terminology and ambiguous descriptions. Their principal value is therefore in consistent large-scale analysis; individual classifications and findings based on small categories carry greater uncertainty.

Attribution of reported consequences to turbulence – All occurrences in the dataset involve turbulence, but an injury, aircraft damage or operational event reported in the same occurrence was not necessarily caused solely by the turbulence encounter. Manual validation reduced this uncertainty for occurrences involving the highest-severity consequences, but equivalent case-by-case validation was not performed for all lower-severity events. Consequently, the results support an association between turbulence and the reported consequences but do not establish causality in every occurrence. The resulting counts may include some consequences to which other factors contributed.

Representativeness of the ECR sample – The ECR provides broad coverage of occurrences reported through the European occurrence-reporting system, including events involving European operators and operations within or connected to EASA Member States. Nevertheless, it is not a statistical sample of all EU carriers or all flights to, from or within Europe. Reporting volumes and completeness may differ between Member States, operators and types of operation. This limits the representativeness of operator, State and region-specific comparisons. The ECR results provide a strong European perspective on reported turbulence occurrences, but they should not be interpreted as demonstrating that every part of European commercial aviation is represented in the same proportion as its operational exposure.

Identification of turbulence-related ECR occurrences – The ECR identification methodology combines structured queries, narrative keyword searches and LLM validation. This approach improves coverage beyond the structured taxonomy alone, but an occurrence that is neither correctly classified nor retrieved by the keyword catalogue cannot reach the LLM-validation stage. Relevant occurrences may therefore be missed when narratives describe only the effects of turbulence or use terminology not covered by the search. The high manual-validation accuracy supports the precision of the candidate-classification stage but does not measure the recall of the complete retrieval process. The resulting ECR sample may therefore underestimate the absolute number of reported turbulence occurrences, particularly in reporting contexts where turbulence is not stated explicitly.

7.2.2. Recorded flight data

Composition of the recorded flight data sample – The recorded flight dataset contains approximately 4.4 million flights from six airlines, providing a strong basis for identifying aggregate patterns within the sample. However, a large sample size does not by itself ensure representativeness. Short-haul operations predominate, approximately 99% of flights involve narrow-body aircraft, and the A320 and B737 families account for most of the data. This composition particularly affects results by flight phase, route type and aircraft response. The proportion of turbulence episodes occurring in cruise may differ in a sample containing more long-haul operations, while the RMSg intensity distribution may change with a different aircraft-type mix.

Limited availability of aircraft dynamic parameters – The turbulence-identification methodology relies primarily on vertical acceleration because parameters such as control-surface deflections, angle of attack,

pilot inputs and detailed autopilot commands are not consistently decoded in the available dataset. Consequently, the high-pass filter cannot distinguish every turbulence-induced response from manoeuvres or automatic flight-control actions. This introduces uncertainty into individual detections, particularly near the lower detection threshold, and may produce false-positive or missed events. The large dataset supports the aggregate patterns identified, but individual episodes cannot always be confirmed as turbulence without additional dynamic parameters.

Separation of turbulence from aircraft manoeuvres – High-pass filtering removes a substantial proportion of the low-frequency acceleration associated with aircraft manoeuvres, but it cannot guarantee complete separation in every flight. Residual manoeuvre-related dynamics may be identified as turbulence, while slowly varying turbulence responses may be attenuated. The effect is expected to be most relevant for detections close to the lower RMSg threshold. This introduces uncertainty into the exact number of light episodes, although the large-scale patterns observed across millions of flights are less dependent on any individual detection.

Intensity represents aircraft response rather than atmospheric turbulence – RMSg measures the vertical acceleration response of the aircraft. That response is influenced by the atmospheric disturbance as well as aircraft mass, configuration, airspeed, altitude and aircraft-specific dynamic characteristics. The same atmospheric turbulence may therefore produce different RMSg values under different operating conditions or in different aircraft. This limitation has a substantial impact on the interpretation of intensity level. The categories are suitable for comparing the magnitude of the recorded aircraft response within the adopted methodology, but they do not provide an aircraft-independent measurement of atmospheric turbulence. They also cannot be directly compared with the subjective intensity categories reported in the ECR. Section 9.1 presents a specific recommendation to extend the turbulence identification methodology to address this limitation.

Absence of meteorological context – The recorded flight data are not linked to weather information. Turbulence episodes therefore cannot be classified reliably as clear-air, convective, terrain-induced or another turbulence type. This prevents the turbulence-type findings obtained from the ECR from being independently validated using recorded flight data. It also means that explanations involving particular meteorological mechanisms remain hypotheses based on the ECR, flight phase, altitude and relevant literature.

Dependence on analytical definitions regarding Nz-range – The relationship between intensity and Nz-range is partly inherent in the methodology because both are derived from the vertical-acceleration signal. The wider Nz range observed at higher RMSg levels should therefore not be treated as fully independent evidence of a separate physical effect. The five-minute threshold used to aggregate individual detections into episodes also affects the number and duration of identified episodes. A shorter threshold would

produce more, shorter episodes, while a longer threshold would merge more detections. This has a direct effect on indicators expressed per episode but does not alter the underlying recorded acceleration signal.

Flight-phase boundaries and the late-cruise peak – Episodes are assigned to a flight phase using defined operational boundaries and the midpoint of the episode. Detections close to top of descent may consequently be assigned either to cruise or descent depending on the selected boundary. This has limited effect on the overall number of detected episodes but introduces uncertainty into the precise size and location of the late-cruise peak. The broader finding that turbulence is concentrated towards lower altitudes and the later stages of flight is less sensitive to this boundary than the specific interpretation of the peak near top of descent.

Aircraft generation as a proxy for weather-radar technology – The actual weather-radar configuration of each aircraft is unavailable. Aircraft generation was therefore used as a proxy for manual or automatic radar tilt and gain management. However, aircraft within the same generation may have different systems or retrofits, while aircraft generation may also be associated with operator, route and fleet differences. The observed difference between the aircraft groups supports weather-radar capability as a plausible explanation for the late-cruise pattern, but it does not demonstrate that radar technology caused the difference. The conclusion should therefore be presented as a hypothesis requiring confirmation using actual airframe-level equipment information.

7.2.3. Data Governance (DaGo) constraints

The Data4Safety Data Governance framework limits the level of detail at which some recorded-flight results can be disclosed. These restrictions do not necessarily reduce the validity of the aggregate calculations that satisfy the representativeness requirements, but they limit the ability to investigate variation within the dataset and to present supporting evidence at a more granular level.

In particular, the recorded flight data cannot be divided by individual aircraft type or consistently analysed by wide-body versus narrow-body operation. This prevents the study from separating aircraft-type effects from differences in route, altitude, flight phase or measured aircraft response. Route-type analysis also cannot be presented for the recorded flight dataset, limiting direct comparison with the ECR short- and long-haul results.

The geographical analysis is restricted to a high level, and grid cells that do not satisfy the disclosure requirements are removed. The resulting maps therefore provide an incomplete representation of the underlying geographical distribution. Areas without displayed data must not be interpreted as areas without turbulence, and the maps are suitable for identifying only broad geographical patterns rather than precise hotspots or comparative regional exposure.

7.2.4. Scope and results aggregation

Geographical, operational and temporal scope – The study concerns commercial air transport operations represented in European occurrence reporting and in the recorded flight data supplied by participating European airlines. The findings may not represent regions, climates, aircraft fleets or operational practices that are poorly represented or absent from these datasets. The results should therefore not be extrapolated directly to global aviation.

The temporal coverage also differs between data sources: the ECR covers 2015–2025, ECR analyses requiring exposure data cover 2019–2025, and recorded flight data cover 2023–2025. Comparisons between the sources may therefore reflect temporal differences as well as differences in reporting and measurement. Findings supported independently by both datasets are more robust, while differences between them should not be attributed to a single cause.

Aggregate comparison rather than occurrence-level data linkage – The ECR and recorded flight data were compared at aggregate level; individual ECR reports were not linked to the corresponding recorded flights. It is therefore not possible to compare reported and measured intensity for the same encounter, determine which measured episodes resulted in a report, or validate flight-data-derived consequential events against the associated occurrence narrative. The two sources provide complementary perspectives, but their comparison cannot produce an occurrence-level reporting probability or establish direct equivalence between their intensity scales.

Observational nature of the analysis – The study identifies distributions, associations and recurring patterns but does not constitute a controlled causal analysis. Factors such as aircraft type, route, flight phase, cabin activity, turbulence type and reporting practice may be interrelated. Consequently, explanations proposed for findings such as the higher reported injury share in clear-air turbulence or the late-cruise difference between aircraft generations should be understood as operationally plausible interpretations supported by the available evidence, rather than isolated causal effects.

7.2.5. Exposure data

The Eurocontrol flight volumes provide the closest available denominator for calculating ECR occurrence rates, but they cannot be matched exactly to the population of flights that may generate ECR reports. Eurocontrol includes overflights by external operators that may not be subject to the same reporting obligations or reporting practices as European operators. This can slightly overestimate the exposure denominator and consequently underestimate ECR occurrence rates per flight. The expected effect is marginal and does not affect the principal qualitative findings, but the resulting values should be treated as approximate reporting rates.

Conversely, the ECR may contain reports concerning flights operated entirely outside EASA Member States airspace, either from EU operators or voluntary reports, whereas such flights are absent from the Eurocontrol exposure dataset used in the study. These occurrences account for less than 5% of the relevant

sample and were removed when calculating exposure-normalised metrics¹⁸. This filtering substantially controls the potential mismatch and avoids the need to make assumptions about why an individual occurrence outside the exposure area was included in the ECR.

The exposure data provide aggregate flight counts and do not reproduce the exact operator, aircraft, route, flight-phase or altitude distribution of the ECR occurrences. Consequently, ECR distributions by flight phase and altitude are not exposure-normalised and cannot be interpreted as the probability of encountering turbulence in each phase or altitude band. Recorded flight data provide the more appropriate source for exposure-based conclusions in these dimensions.

7.2.6. Consequential events

The ECR consequential-event analysis relies on enhanced Event Type information derived from structured ECCAIRS2 fields and occurrence narratives. The analytical groups are not mutually exclusive, and a single occurrence may contain several aircraft-state, injury and operational events. Some groups, such as diversions or precautionary landings, may reflect successful risk-reduction decisions rather than adverse safety outcomes. The reported proportions therefore describe how frequently each event was identified in turbulence-related reports; they should not be added together or interpreted as mutually exclusive accident probabilities.

For recorded flight data, only consequential events that could be derived from the available parameters were analysed. Their identification depends on predefined thresholds and time windows around each turbulence episode. Temporal proximity does not establish that turbulence caused the event. This is particularly important for TCAS resolution advisories and autopilot disengagements, which may result from pilot action, traffic conditions or other operational factors. Repeated autopilot disengagements support the identification of an association requiring further examination, but they do not by themselves demonstrate that the autopilot was unable to cope with turbulence.

7.2.7. Bow tie analysis

The bow tie analysis depends on the quality and completeness of the turbulence-related ECR occurrences and the information contained within the associated narratives. These reports were not written with a barrier analysis in mind and may lack information on barriers that operated normally or effectively prevented further escalation.

¹⁸ Note that even if a custom exposure dataset were constructed, an exact correspondence would still not be achievable. Because reporting to the ECR is voluntary for operators and flights with no legal reporting obligation, the true population of flights from which ECR occurrences originate is not fully known or stable, and therefore cannot be reliably replicated in an exposure dataset.

By construction, the ECR dataset contains reported turbulence encounters that occurred. Encounters successfully avoided through forecasting, tactical planning or other preventive actions are generally not represented. The analysis is therefore weighted towards barriers that act during or after the encounter, while barriers intended to avoid the encounter show comparatively high failure rates. This is a consequence of the dataset selection and must not be interpreted as evidence of poor barrier reliability or as a measure of the operational effectiveness of preventive barriers.

The assessment also simplifies the occurrence sequence. Consequential events are not mutually exclusive, and several barrier actions may operate within the same occurrence, although only the action associated with the stopping barrier was retained for the occurrence-level classification. A “stopped” status was assessed against the potential accident outcome associated with the common reference KRA, aircraft upset. It indicates that the selected barrier prevented further escalation along that reference sequence; it does not mean that every consequence was prevented. The results are therefore suitable for identifying recurrent barrier-action patterns and the defensive layers evidenced in reported event sequences.

8 CONCLUSIONS

The present study has examined in-flight turbulence and its effect on the safety of commercial aviation operations in Europe over the period 2015 to 2025, with the analysis concentrated on the years 2019 to 2025, for which data coverage is most complete. The study used data drawn from two separate safety data sources, namely text-based occurrence reports from the European Central Repository (ECR) and recorded flight data from a range of European operators. A summary of the main findings and limitations of the study can be found in Chapter 7. The conclusions from this study are presented hereinafter. Those related to in-flight turbulence are presented in Section 8.1, while Section 8.2 presents a set of conclusions on the cooperation with the Data4Safety programme and its role as an enabler of the present work.

8.1. In-flight turbulence

Conclusions on data processing and turbulence identification

A substantial part of the effort in this study was devoted to data processing and turbulence identification from the data, and a first conclusion is that this preparatory work is time-consuming but critical to be able to analyse data, as it laid the foundation for the findings. The principal challenge was the very different nature of the two data sources, one is a body of textual occurrence reports and the other contains a large volume of recorded flight data, such that no single processing and turbulence identification approach could serve both. Each data source was therefore processed through a dedicated, purpose-built methodology suited to the data structure, as set out in Chapter 4.

For the ECR data, the analysis demonstrated the value of advanced analytics, and specifically of large language models (LLMs), in the interpretation of safety occurrence reports. The use of LLMs allowed the reports to be treated consistently and at speed across a large dataset, improved the completeness of the information drawn from each report, and, most significantly, made it possible to extract information required for the study from the free-text narratives that was otherwise absent from any taxonomy field, such as the turbulence type. The conclusion is that LLM-based processing was a key enabler of the ECR data analysis, with its applicability extending well beyond the study of turbulence-related occurrences to provide a valuable approach for the interpretation of occurrence data.

For the recorded flight data, the study established that industry data of this kind can provide a reliable baseline of physical exposure to turbulence, against which the reported occurrences can be interpreted, provided a suitable identification method is in place. The dedicated methodology developed in this study, based on the root mean square of the vertical load factor (N_z) signal, showed two components to be decisive. Firstly, a high-pass filter that distinguishes the aircraft's response to turbulence from that produced by intentional manoeuvres, so that manoeuvres are not misidentified as turbulence. Secondly, the consolidation of individual turbulence events into coherent turbulence episodes, which provides the natural unit for characterising an encounter.

In conclusion, this study represents the first attempt of its kind to combine ECR occurrence reports with recorded flight data to characterise in-flight turbulence, and it is, to the best of the author's knowledge, unprecedented in terms of the volume and diversity of data used within it. This is a significant step forward: rather than relying on either the reported record or the flight data alone, the study draws on both sources, across a large and varied body of European flights. Its central lesson is that the two sources are complementary. Neither could, on its own, have produced the picture presented here, and it is the comparison of ECR-reported occurrences with aggregate measurements of turbulence exposure and aircraft response that gives the findings their strength. In demonstrating this capability, the study has validated an approach that could be followed for other safety issues as well. It shows that the data assets made available through the Data4Safety programme have reached a level of maturity capable of supporting research projects for the benefit of, and in collaboration with, the European aviation industry, as discussed in more detail in Section 8.2.

Conclusions on turbulence characterisation

The characterisation of turbulence encounters supports several conclusions that go beyond the individual findings.

1. Cruise represents the lowest frequency of turbulence per unit of flight time, yet it dominates the reported occurrences, which means the likelihood that an encounter results in a reportable consequence is far higher in cruise than its frequency based on recorded flight data would suggest. Two distinct "risk profiles" emerge from this finding. The first is the low probability, high consequence encounter: severe, and often clear-air turbulence, which is rare on a per flight hour basis but is disproportionately likely to cause harm when it occurs. The second, and more easily overlooked, is the high probability, lower consequence encounter: light turbulence, although of light intensity still so frequent that, in combination with an exposed cabin and the other factors discussed below, it still accounts for a meaningful share of consequential events. Managing turbulence therefore means addressing both the rare severe encounters and the cumulative effect of the common light encounters.
2. For the individual flight, turbulence is infrequent and predominantly benign: it affects a minority of flights, is overwhelmingly of light intensity, and rarely damages the aircraft, which is itself an important reassurance about the safety of flight operations. The data shows implication for flight safety by turbulence in well-defined circumstances: in case of unrestrained occupants, cabin service in progress, and turbulence that could not be anticipated. Turbulence intensity does play a role, since stronger encounters are more likely to cause injuries, but the current study shows that intensity is not the dominant factor for injuries. Whether an encounter causes injuries depends to a large extent on whether the cabin was timely prepared for it. This shift in perspective presents an opportunity for mitigation, as turbulence is transformed from an uncontrollable atmospheric hazard to a challenge that can be largely managed through timely identification of turbulence, avoidance measures and cabin preparation, which are factors that can be proactively addressed.

3. The most effective mitigation strategies are often among the simplest, yet they vary depending on the specific group at risk, highlighting the importance of targeted approaches for optimal impact. For passengers, the study shows that turbulence-related injury is driven by not wearing seatbelts, because unrestrained passengers are markedly more likely to be injured and to be injured seriously. So, consistent seatbelt use is the single intervention with the greatest effect on passenger injury. Cabin crew, however, cannot be protected in the same way, since their duties require them to be unrestrained and moving through the cabin during large portions of the flight. It is precisely during cabin service and while being in the galley that they are most often injured due to turbulence. For this group the mitigation is in timely information of imminent turbulence and preparedness. The suspension of cabin service and the securing of the galley and cabin ahead of an anticipated turbulence encounter depends on the earlier and more reliable turbulence information discussed below.
4. Clear-air turbulence carries a higher injury likelihood, not because it is more intense but because it is hard to anticipate, cannot be seen on weather radar and occurs predominantly in the cruise phase when the occupants are most exposed (e.g. not wearing seatbelts, walking/standing in the cabin). The observed clustering of turbulence episodes during late cruise, coupled with their association with weather radar technology, highlights a key opportunity: where turbulence can be anticipated, proactive measures can be taken to mitigate its impact on the occupants and aircraft. Consequently, a primary operational strategy, in conjunction with use of seatbelts, is to provide as early and reliable turbulence information as feasible, particularly during descent phases and in aircraft with older weather radar equipment.
5. Clear-air turbulence is the turbulence type identified in this study as being associated with an increased likelihood of injury, and it is also the turbulence type for which the relationship with climate change is most consistently established. Observational evidence indicates that the atmospheric conditions associated with CAT are already changing, while projections indicate that severe CAT could become approximately two to three times more frequent over the period 2050–2080 [25]. Convective turbulence is also expected to intensify in a warmer and moister atmosphere, although projections remain considerably more uncertain [27]. Climate change therefore has the potential to amplify the safety concern identified in this study by increasing exposure to a turbulence type that is particularly difficult to anticipate and that occurs predominantly in cruise, where cabin activity and occupant exposure increase the likelihood of injury. This reinforces the need for continued improvement in turbulence detection and forecasting, particularly for CAT, and in onboard weather-radar technology for the management of convective turbulence. The present study establishes a baseline against which future changes in turbulence exposure and its associated consequences can be monitored and assessed.

Conclusions on consequential events and safety barrier performance

The analysis of consequential events shows that the effects associated with turbulence vary in nature and severity and become more frequent as turbulence intensity increases. In the ECR dataset, overspeed is the most frequently reported consequence, occurring in approximately one quarter of turbulence-related occurrences, followed by injuries, aircraft upset and operational consequences such as diversions. Aircraft damage and loss of separation are comparatively rare. The recorded flight data similarly show that consequential event rates increase substantially with turbulence intensity. Autopilot disengagement is the most frequently detected event, while exceedances of flight envelope protection limits remain rare.

The safety barrier assessment demonstrates that preventing escalation does not depend on a single barrier but on a layered structure of technical, operational and human action barriers. Because the ECR dataset, by nature, contains only reports on turbulence encounters that occurred and generally does not include occurrences of avoided turbulence, the preventive barriers appear to fail in most reported occurrences. Therefore, the assessment is weighted towards the mitigation and recovery layers, providing a one-sided view and limiting to fully assess the effectiveness of preventive barriers. Within the analysed occurrences, procedures and crew actions most frequently stopped further escalation, supported by situational awareness. Aircraft design and flight envelope protection, warning systems and late-recovery measures provided additional mitigation or remained available to prevent progression towards the reference high-severity potential accident outcome associated with the aircraft upset Key Risk Area.

The results also show that a reported consequence may occur even when relevant barriers operate successfully, because different barriers address different effects of the encounter. Aircraft state events such as overspeed, aircraft upset and level bust are primarily limited by structural and flight envelope protection, crew monitoring and warning system responses. Flight envelope protection may function successfully even when an occupant injury occurs. Relevant barriers in relation to turbulence-related injuries include the use of seatbelts (restraints) and timely securing the cabin for turbulence (e.g. suspending cabin service and performing a cabin safety check). These actions reduce the likelihood and severity of injury in case of turbulence.

The principal operational conclusion is that effective turbulence management requires coordinated use of available turbulence information, timely flight deck and cabin preparation, occupants using restraints, aircraft protections and recovery capabilities.

8.2. Conclusions on the cooperation with D4S in research studies

The directed study was conducted as part of the ALBATROS project. This study marks the D4S programme's first involvement in a research project, paving the way for future collaborations and applications of the programme's capabilities in aviation safety research.

The D4S programme enhances aviation safety insights – In conclusion, the D4S programme has proven particularly useful in providing valuable data on in-flight turbulence occurrences, insight into its circumstances and safety effects. More broadly, the D4S programme provides significant value for identifying, characterising and understanding aviation safety risks. Its exploitation in research projects addressing aviation safety-related topics can provide valuable insight into the factors influencing safety performance, emerging trends, levels of exposure to specific risks, and the effectiveness of mitigation measures. This provides an important reference against which future developments can be assessed.

The maturity of the D4S data assets now supports research-grade analysis – A central conclusion of this study is that the data assets made available through the D4S programme have reached a level of maturity at which they can support a research study of this kind. This was the first occasion on which those assets were used for such a purpose, and they proved capable of sustaining a complete analysis, from the identification and processing of turbulence from two very different sources through to a characterisation and analysis of consequential events and safety barrier performance. A key demonstration of that maturity is the programme's ability to bring together complementary sources: the ECR occurrence reports, which captures the reported occurrences, their circumstances and consequences, and the recorded flight data, which measures the characteristics and effects of turbulence. By combining these sources, the programme enables a comprehensive analysis, allowing for comparison and reconciliation of the data. Notably, neither source could have produced the presented findings in this study on its own. A further strength lies in the scope of the underlying data: the analysis draws on occurrence reports and flight data from a broad range of European operators, which lends the results a degree of representativeness for European operations that few other data sources could offer, and which reinforces the value of the programme as a basis for safety research at a European level.

Interdisciplinary collaboration is key to meaningful results – The current study has demonstrated that combining data analytics expertise with aviation safety and operational knowledge is essential to producing reliable, meaningful and actionable results. The directed study was successfully completed through a joint effort involving subject matter experts in data analytics, aviation safety, flight dynamics, and flight operations. The study demonstrated that advanced data-processing capabilities and operational/safety expertise are both required to understand the context behind the data, to assess the relevance and validity of identified patterns, and to translate analytical findings into an operationally meaningful context.

Data accessibility is key in unlocking the programme's full potential – The current directed study was subject to restrictive data governance rules, which imposed limitations on the availability and sharing of certain data and findings, thereby diminishing the usability and value of the programme's outcomes. The value of the D4S programme depends to a large extent on the availability of the underlying data and analytical results to support meaningful analyses, verification and validation of results, and reproducibility, subject to appropriate data-governance constraints. It is important that analysts and researchers have more

access to de-identified or otherwise appropriately protected data that retains sufficient information to support meaningful analysis (while safeguarding sensitive information).

Effective analysis relies on comprehensive data access – Experience from past safety analyses has shown that reviewing narrative data helps to better understand the way occurrences are reported and the factors that played a role in the event. This review often results in changing the queries for data extraction or leads to additional data analyses. It also helps to understand the underlying factors in events that cannot be identified by e.g. AI tools or that are not reported as factors in the database taxonomy. Ensuring subject matter experts have appropriate access to the (processed) data is therefore essential for effective and efficient analysis.

9 RECOMMENDATIONS

9.1. Recommendations for future research

This section proposes recommendations and considerations for future research with the aim to further increase the knowledge and scientific evidence on turbulence and its effects on flight safety. Building on the findings presented in Chapters 5 and 6, and the limitations identified in Section 7.2, a series of recommendations for future research has been compiled. These recommendations are intended to address the specific gaps and challenges identified through the present study, while also outlining opportunities to extend the scope, applicability, and impact of the research into turbulence in future studies.

1. **Fuse ECR data and recorded flight data** – Linking recorded flight data to specific ECR occurrences would enable an additional layer of analysis to evaluate the influence of the reporting biases in each dataset, compare them directly against one another, and confirm or dismiss some of the hypotheses identified in this study related to the relationship between the two datasets, such as the difference in overall observation frequency and the role of intensity level introduced in Section 5.2. This link is also the natural way to overcome the fact that the ECR data does not record the physical magnitude of a turbulence encounter, so the reported intensity cannot presently be correlated against an objective measure. Associating each occurrence with its recorded flight data would supply that missing physical magnitude and allow the reported and measured intensities to be related directly. The benefits would be mutual: ECR reports could be enriched with the detailed temporal evolution and objective magnitude of the event provided by recorded flight data, while the consequential events identified in the recorded flight data could be understood or validated using occurrence reports, leading to more robust conclusions.
2. **Link turbulence episodes in the recorded flight data to contemporaneous meteorological data** – Associate turbulence episodes with satellite or ground-radar meteorological data to assign

turbulence type to the turbulence episodes and to assess any association with convective weather, removing the principal limitation that the recorded flight data carries no meteorological context.

3. **Establish the capacity to determine turbulence type from recorded flight data** – Building on the meteorological linkage described above, a specific and potentially near-term research action would be to establish whether turbulence type can be reliably assigned to turbulence episodes identified in recorded flight data by mapping them against external meteorological observations. Because turbulence type is currently available only in the ECR dataset, establishing this capability would materially extend the range of turbulence characteristics that can be derived from recorded flight data. An initial research question would be whether external meteorological observations, such as EUMETNET OPERA weather-radar products [37] and EUMETSAT satellite observations [38], can be used to reliably map turbulence episodes to the prevailing atmospheric conditions and thereby support the classification of turbulence type and the identification of geographical areas in which different turbulence types predominate. This capability could then be used to classify the recorded flight-data episodes and provide an important basis for subsequent analyses of turbulence intensity, operational context and barrier performance.
4. **Incorporate an EDR-based methodology into the recorded flight data analysis to estimate the intensity of incoming atmospheric turbulence** – Future research should investigate the incorporation of an eddy dissipation rate (EDR)-based methodology into the analysis of recorded flight data. EDR is the standardised metric for turbulence intensity [39] and provides an aircraft-independent measure of the intensity of atmospheric turbulence. Estimating EDR from recorded flight data would therefore enable the intensity of the incoming free-air turbulence to be characterised independently of aircraft type and operational conditions. This would directly address a key limitation of the turbulence identification methodology used in this study, which is based on the RMS of the N_z signal and consequently quantifies the magnitude of the aircraft's response to turbulence rather than the intensity of the turbulence within the surrounding air mass.

This recommendation is also consistent with the findings of the EASA Scientific Committee's Annual Report [1], which discusses the effects of climate change on aviation turbulence and identifies the availability (or lack thereof) of in-flight turbulence measurements, such as EDR values, as a limitation of existing studies. Incorporating an EDR-based approach alongside the N_z -based methodology used in the present work would therefore provide a more comprehensive characterisation of turbulence events by allowing the incoming atmospheric turbulence and the resulting aircraft response to be assessed separately. This would help distinguish the characteristics of the atmospheric conditions from aircraft-specific effects and improve the robustness and transferability of the resulting turbulence analysis.

5. **Repeat the analyses once more flight data becomes available** – Repeat the geographical and route-type analyses based on recorded flight data as additional operators and flights become available within the D4S programme and data governance constraints allow for a more detailed breakdown. As D4S is in its development phase, the amount of available data is expected to increase progressively, reducing many of the restrictions encountered in the present study. Repeating these analyses with a larger dataset would therefore support the robust identification of regional turbulence hotspots and provide meaningful insights into differences across regions, routes, and aircraft types.
6. **Repeat the study over time and monitor turbulence continuously through safety performance indicators** – Beyond repeating individual analyses as more data becomes available, the study as a whole should be revisited periodically to track how turbulence trends evolve. To support this, it is recommended that the analytics developed in this study be operationalised as safety performance indicators (SPIs) within the D4S platform, so that turbulence can be monitored continuously. This would facilitate a transition from European safety research to ongoing, real-time safety monitoring, enabling proactive identification of emerging turbulence trends and risks.
7. **Improve the attribution of consequential events in recorded flight data to turbulence** – Future work should investigate methods to distinguish consequential events directly associated with turbulence from events that merely coincide with a turbulence encounter. This could include case-by-case validation using the potential fusion between ECR data and recorded flight data, together with additional recorded flight parameters describing the aircraft state, aircraft response, and pilot inputs.
8. **Expand the consequential events in the analysis of recorded flight data** – Future work could expand the number of consequential events in the analysis of recorded flight data to provide a more comprehensive assessment of the operational and safety effects associated with turbulence encounters. In addition to the events analysed in the present study, other relevant consequences could be investigated, such as level busts, unstable approaches, stall warnings or stick-shaker activations, and significant flight path or altitude deviations.
9. **Extend the bow tie analysis** – Future research should refine the bow tie analysis developed in ALBATROS Task 2.1 by assessing the performance of the operational barriers identified in the bow tie using ECR data. In contrast to the ERCS barrier types, which represent barriers at a higher level of abstraction, the ALBATROS Task 2.1 bow tie provides a more detailed representation of the operational barriers and their role in preventing or mitigating turbulence-related occurrences. ECR narratives could therefore be used to assess which barriers were present, whether they were effective, and at what stage of the event they acted or failed to act.

The analysis should also be stratified by operational context, including clear-air versus convective turbulence, turbulence intensity, and phase of flight, to identify whether barrier performance and barrier pathways differ across contexts. Where available, ECR narratives could be combined with meteorological data, recorded flight data, and other operational sources to improve the assessment of event timing and the opportunities for successful barrier intervention. This would enable a more detailed analysis of the ECR data and provide greater insight into the effectiveness and context-dependency of individual operational barriers.

10. **Analyse injuries at the individual level in the ECR data** – In the present study, injury information from the ECR was analysed at the aggregate level of the occurrence rather than at the individual injury. A single occurrence may involve several injuries with different circumstances, which can be obscured when treated in aggregate. Future work should derive and analyse injury information at the individual injury level, so that the activity, location, affected person and severity associated with each injury can be tracked separately within an occurrence. This finer granularity would allow the injury-related findings, in particular those concerning activity, location and the role of restraint, to be established more precisely.
11. **Build custom exposure denominators for the ECR data** – Where feasible, construct exposure denominators for the ECR data to enable a per flight phase and per altitude normalisation of the occurrence data.
12. **Investigate further the role of weather radar technology as a driver of the late-cruise peak** – The association between weather radar technology and the late-cruise concentration of turbulence episodes remains a hypothesis supported by an indirect proxy, and it warrants further research. Beyond establishing the actual weather radar configuration at airframe level, future work should examine the factors that could influence the performance of weather radar technology, including crew proficiency in handling of the weather radar, workload during the cruise-to-descent transition, and the effectiveness of convective weather depiction, so that the mechanism, and not only the correlation, can be established or ruled out.
13. **Investigate the methodological contribution to the late-cruise peak** – Perform a sensitivity analysis of the cruise-to-descent boundary rule, together with the analysis of frequency of turbulence episodes measured around the top of descent, to establish how much of the late-cruise concentration of turbulence episodes is the result of the flight phase boundary definition rather than the actual prevalence of turbulence.
14. **Characterise the drivers of the break in the trend of ECR data in 2023** – Investigate the contributions of the ERCS mandate, Key Risk Area field population and increased awareness or any

other changes in reporting practices, to understand the trend break in the ECR data sample observed from 2023 and to support the interpretation of the ECR data in other studies.

9.2. Recommendation to airlines

Airlines are advised to take note of the results of the directed study on in-flight turbulence. The findings and results could be a starting point for an airline's own review to address the risk of turbulence. The bow tie model may be used by airlines to identify factors and events for which data needs to be collected within the airline through for example Flight Data Monitoring (FDM) or occurrence reporting systems.

Furthermore, airlines are encouraged to evaluate the applicability of the methodology presented in this study for identifying and analysing turbulence episodes using recorded flight data within their Flight Data Monitoring (FDM) programmes.

9.3. Recommendations on D4S capabilities for future research

The D4S programme offers substantial potential for future research projects – Researchers should leverage the D4S programme in future research projects to enhance aviation safety analyses and understanding of aviation safety risks. Building on the successful collaboration with EASA and D4S within the ALBATROS project, it is recommended that the D4S programme's capabilities, data, and analytical outputs are made available for the purpose of future aviation safety research.

The multidisciplinary approach is key to success – Future exploitation of the D4S programme should continue to apply a multidisciplinary approach, bringing together data analysts and subject matter experts in aviation safety, flight dynamics, and flight operations. This combination of expertise is an essential requirement for generating results that are not only technically sound, but also relevant, valid, and actionable from an operational and safety perspective.

Improved data access is essential – Providing subject matter experts with access to de-identified occurrence narratives and contextual occurrence data would enable more comprehensive and higher-quality safety analyses. Appropriate safeguards, including non-disclosure agreements and other data-protection measures, can be implemented to ensure that the use of such information remains consistent with applicable privacy and confidentiality requirements. A well-defined process for requesting, accessing, and using data would further increase the programme's added value in research and flight safety.

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Appendix A SAFETY PERFORMANCE INDICATORS

This appendix contains the list of Safety Performance Indicators (SPIs) and pseudocodes implemented to compute the various SPIs presented, with notes related to their definition and implementation.

Appendix A.1 List of SPIs

SPIs for ECR data

General turbulence observation frequency

What is the observed frequency to turbulence-related occurrences?

ID	Safety Performance Indicator
E.1.1	Number of turbulence occurrences
E.1.2	Number of turbulence occurrences as a percentage of the total ECR occurrences
E.1.3	Number of turbulence occurrences per 1,000 flights

Intensity level

What is the breakdown by intensity level?

ID	Safety Performance Indicator
E.2.1	Number of turbulence occurrences by intensity level as a percentage of turbulence occurrences
E.2.2	Number of turbulence occurrences by intensity level per 1,000 flights

Damage severity level

What is the breakdown by damage severity level? How many events lead to damage to the aircraft?

ID	Safety Performance Indicator
E.3.1	Number of turbulence occurrences by damage severity level
E.3.2	Number of turbulence occurrences by damage severity level as a percentage of turbulence occurrences

Are the two correlated? Does higher intensity lead to higher damage?

ID	Safety Performance Indicator
E.4.1	Number of turbulence occurrences by intensity level and damage severity as a percentage of turbulence occurrences

Injuries

How commonly does turbulence result in injuries?

ID	Safety Performance Indicator
E.5.1	Number of turbulence occurrences with injury as a percentage of turbulence occurrences
E.5.2	Number of turbulence occurrences with injury per 1,000 flights

How severe are the injuries caused?

ID	Safety Performance Indicator
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E.6.1	Number of turbulence occurrences with injury, by injury severity level as a percentage of turbulence occurrences
E.6.2	Number of turbulence occurrences with injury, by injury severity level per 1,000 flights

Is intensity level correlated with injury severity level?

ID	Safety Performance Indicator
E.7.1	Number of turbulence occurrences with injury by turbulence intensity and injury severity level as a percentage of turbulence occurrences

What is the distribution of turbulence related injuries among pilots, cabin crew, passengers?

ID	Safety Performance Indicator
E.8.1	Distribution of turbulence related injuries amongst passengers, flight crew, and cabin crew, as a percentage of turbulence occurrences

What is the correlation between injury severity and injuries among pilots, cabin crew, passengers?

ID	Safety Performance Indicator
E.9.1	Number of turbulence occurrences with injury among pilots, cabin crew, passengers by severity as a percentage of turbulence occurrences

What is the distribution of turbulence related injuries per location inside the aircraft?

ID	Safety Performance Indicator
E.10.1	Distribution of turbulence related injuries per location inside the aircraft as a percentage of turbulence occurrences

What is the correlation between injury severity and injuries per location inside the aircraft?

ID	Safety Performance Indicator
E.11.1	Number of turbulence occurrences with injury per location inside the aircraft by severity as a percentage of turbulence occurrences

What is the distribution of turbulence related injuries per activity inside the aircraft?

ID	Safety Performance Indicator
E.12.1	Distribution of turbulence related injuries per activity inside the aircraft as a percentage of turbulence occurrences

What is the correlation between injury severity and injuries per activity inside the aircraft?

ID	Safety Performance Indicator
E.13.1	Number of turbulence occurrences with injury per activity inside the aircraft by severity as a percentage of turbulence occurrences

Turbulence type

What is the breakdown by turbulence type?

ID	Safety Performance Indicator
E.14.1	Number of turbulence occurrences by turbulence type as percentage of turbulence occurrences

Does the breakdown change if we consider only encounters with injuries?

ID	Safety Performance Indicator
E.15.1	Number of turbulence occurrences with injury by turbulence type as a percentage of turbulence occurrences with injury

Does the breakdown by injury severity level change for different turbulence types?

ID	Safety Performance Indicator
E.16.1	Number of turbulence occurrences with injury by turbulence type and injury severity level as a percentage of turbulence occurrences with injury

Is turbulence type correlated with turbulence intensity?

ID	Safety Performance Indicator
E.17.1	Number of turbulence occurrences by turbulence type and intensity level as a percentage of turbulence occurrences

Altitude

What is the breakdown by flight level (FL)? Are some altitude (FL) bands more prone to turbulence than others?

ID	Safety Performance Indicator
E.18.1	Number of turbulence occurrences by altitude (FL) as a percentage of turbulence occurrences

Does intensity level vary with altitude?

ID	Safety Performance Indicator
E.19.1	Number of turbulence occurrences by altitude (FL) and intensity level as a percentage of turbulence occurrences

Does the breakdown by turbulence type vary with altitude?

ID	Safety Performance Indicator
E.20.1	Number of turbulence occurrences by altitude (FL) and turbulence type as a percentage of turbulence occurrences

Geographical information

What is the breakdown by State Area of Occurrence?

ID	Safety Performance Indicator
E.21.1	Number of turbulence occurrences by State Area of Occurrence as a percentage of turbulence occurrences
E.21.2	Number of turbulence occurrences by State Area of Occurrence per 1,000 flights

Are any regions more prone to specific types of turbulence?

ID	Safety Performance Indicator
E.22.1	Number of turbulence occurrences by State Area of Occurrence and turbulence type per 1,000 flights

Flight phase

What is the breakdown by flight phase?

ID	Safety Performance Indicator
E.23.1	Number of turbulence occurrences by flight phase as a percentage of turbulence occurrences

Are some flight phases more prone to having more/less intense turbulence?

ID	Safety Performance Indicator
E.24.1	Number of turbulence occurrences by flight phase and turbulence intensity as a percentage of turbulence occurrences

What is the breakdown by flight phases for turbulence occurrences with injuries?

ID	Safety Performance Indicator
E.25.1	Number of turbulence occurrences with injuries by flight phase as a percentage of turbulence occurrences

Is there a relation between flight phase and turbulence type?

ID	Safety Performance Indicator
E.26.1	Number of turbulence occurrences by flight phase and turbulence type as a percentage of turbulence occurrences

Route type

Are some routes more prone to turbulence than others?

ID	Safety Performance Indicator
E.27.1	Number of turbulence occurrences by route origin/destination as percentage of turbulence occurrences

Is intensity level correlated with route type?

ID	Safety Performance Indicator
E.28.1	Number of turbulence occurrences by route origin/destination by turbulence intensity as percentage of turbulence occurrences

Is turbulence type correlated with route type?

ID	Safety Performance Indicator
E.29.1	Number of turbulence occurrences by route origin/destination by turbulence type as percentage of turbulence occurrences

Seasonality

Is there a clear seasonality in the number of occurrences?

ID	Safety Performance Indicator
E.30.1	Seasonality of number of turbulence occurrences per 1,000 flights

Is there a clear seasonality in the number of occurrences with injuries?

ID	Safety Performance Indicator
E.31.1	Seasonality of number of turbulence occurrences with injuries per 1,000 flights

Is there a clear seasonality in the number of occurrences when broken by turbulence type?

ID	Safety Performance Indicator
E.32.1	Seasonality of number of turbulence occurrences by turbulence type per 1,000 flights

Safety risk assessment: Consequential events, barriers, and mitigation events

How many of the turbulence occurrences lead to each consequential event, barrier, and mitigation event?

ID	Safety Performance Indicator
E.33.1	Number of overspeed events during/due to turbulence as a percentage of turbulence occurrences
E.34.1	Number of aircraft upset during/due to turbulence as a percentage of turbulence occurrences
E.35.1	Number of level bust during/due to turbulence as a percentage of turbulence occurrences
E.36.1	Number of injured person on board during/due to turbulence as a percentage of turbulence occurrences
E.37.1	Number of aircraft damaged during/due to turbulence as a percentage of turbulence occurrences
E.38.1	Number of aircraft damaged due to dynamic g-loads during/due to turbulence as a percentage of turbulence occurrences
E.39.1	Number of loss of separation during/due to turbulence as a percentage of turbulence occurrences
E.40.1	Number of reduction in safety margins during/due to turbulence as a percentage of turbulence occurrences
E.41.1	Number of operational consequences during/due to turbulence as a percentage of turbulence occurrences

SPIs for recorded flight data

General characterisation

ID	Safety Performance Indicator
F.1.1	Number of turbulent episodes per 1,000 flights
F.1.2	Number of flights with turbulence as a percentage
F.1.3	Average duration of a turbulent episode

Vertical acceleration

ID	Safety Performance Indicator
F.2.1	Distribution of minimum Nz in turbulent episodes
F.2.2	Distribution of maximum Nz in turbulent episodes
F.2.3	Distribution of average Nz in turbulent episodes

Intensity level

ID	Safety Performance Indicator
F.3.1	Number of turbulent episodes by intensity level per 1,000 flights
F.3.2	Number of turbulent episodes by intensity level as a percentage of total episodes
F.3.3	Average duration of turbulent episodes by intensity level
F.3.4	Average Nz range by intensity level
F.3.5	Average number of oscillations per episode by intensity

F.3.6	Average number of events per episode by intensity
F.3.7	Distribution of episode duration by intensity
F.3.8	Distribution of average Nz signal by intensity
F.3.9	Distribution of minimum and maximum Nz signal by intensity
F.3.10	Distribution of average episode oscillation frequency by intensity
F.3.11	Number of episodes per flight by intensity as a percentage of total episodes

Altitude

ID	Safety Performance Indicator
F.4.1	Number of turbulent episodes by altitude (FL)
F.4.2	Number of turbulent episodes by altitude (FL) by flight phase
F.4.3	Distribution of number of episodes by altitude by intensity

Geographical distribution

ID	Safety Performance Indicator
F.5.1	Map of turbulent episodes

Flight phase

ID	Safety Performance Indicator
F.6.1	Number of turbulent events per episode by flight phase
F.6.2	Number of episodes by flight phase as a percentage of total episodes
F.6.3	Number of episodes by flight phase by average flight phase duration
F.6.4	Number of turbulent events per episode by flight phase by intensity
F.6.5	Distribution of average Nz signal value by flight phase
F.6.6	Distribution of Nz range by flight phase
F.6.7	Distribution of episode duration by flight phase
F.6.8	Distribution of minimum and maximum Nz signal value by flight phase
F.6.9	Distribution of turbulence episodes with respect to phase progress by flight phase

Aircraft generation

ID	Safety Performance Indicator
F.7.1	Distribution of episodes by phase progress, by aircraft generation

Seasonality

ID	Safety Performance Indicator
F.8.1	Seasonality of number of turbulence episodes per 1,000 flights
F.8.2	Seasonality of number of turbulence episodes by intensity per 1,000 flights

Consequential events

ID	Safety Performance Indicator
F.9.1	Number of TCAS RA episodes during/due to turbulence per 1,000 turbulence episodes
F.9.2	Number of TCAS RA episodes during/due to turbulence
F.9.3	Number of TCAS RA episodes during/due to turbulence by intensity
F.9.4	Number of TCAS RA episodes during/due to turbulence by flight phase
F.10.1	Number of aircraft upset episodes during/due to turbulence per 1,000 turbulence episodes
F.10.2	Number of aircraft upset episodes during/due to turbulence
F.10.3	Number of aircraft upset episodes during/due to turbulence by intensity
F.10.4	Number of aircraft upset episodes during/due to turbulence by type of upset
F.10.5	Number of aircraft upset episodes during/due to turbulence by flight phase
F.11.1	Number of overspeed due to MMO/VMO exceedance episodes during/due to turbulence per 1,000 turbulence episodes
F.11.2	Number of overspeed due to MMO/VMO exceedance episodes during/due to turbulence
F.11.3	Number of overspeed due to MMO/VMO exceedance episodes during/due to turbulence by intensity
F.11.4	Number of overspeed due to MMO/VMO exceedance episodes during/due to turbulence by flight phase
F.11.5	Distribution of average Mach/CAS during overspeed episodes by intensity
F.11.6	Distribution of maximum Mach/CAS during overspeed episodes by intensity
F.11.7	Distribution of increase in Mach/CAS during overspeed episodes by intensity
F.12.1	Number of autopilot disengagement episodes during/due to turbulence per 1,000 turbulence episodes
F.12.2	Number of autopilot disengagement episodes during/due to turbulence
F.12.3	Number of autopilot disengagement episodes during/due to turbulence by 1,000 turbulence episodes by intensity
F.12.4	Number of autopilot disengagement episodes during/due to turbulence by flight phase as a percentage of total episodes
F.12.5	Number of autopilot disengagement episodes by number of disengagements
F.12.6	Average number of autopilot disengagements by intensity
F.13.1	Number of flight envelope protection limits episodes during/due to turbulence per 1,000 turbulence episodes
F.13.2	Number of flight envelope protection limits episodes during/due to turbulence
F.13.3	Average duration exceeding flight envelope protection limits
F.14.1	Number of passenger discomfort episodes during/due to turbulence per 1,000 turbulence episodes
F.14.2	Number of passenger discomfort episodes during/due to turbulence
F.14.3	Average duration exceeding passenger discomfort limits

Appendix A.2 Notes on SPI definition and implementation

Grouping by time interval

Most SPIs can be computed in two modes: aggregated over the full dataset to provide a static characterisation of the study period as a whole, or aggregated by year to show temporal trends. For the sake of brevity, this distinction is not made explicit in the SPI definitions presented in this appendix. However, both modes of computation are applicable to most indicators.

Breakdown by time intervals (e.g. per year or month) is particularly relevant for exposure-adjusted SPIs. When a rate-per-flight indicator is computed across all years and segmented by a single dimension (such as intensity level), the exposure normalisation adds limited analytical value, because it merely scales the corresponding percentage-based indicator by a constant factor. The per-flight normalisation becomes meaningful when 1) evolution over time is taken into account (allowing changes in rate to be distinguished from changes in traffic volume), 2) geographical breakdowns are examined, or 3) comparing subsets of turbulence events that differ in their segmentation (for example, all turbulence occurrences versus those involving injuries, structural damage, or high-intensity encounters).

Notes specific to the ECR workstream

Notation

Two reference totals are used throughout the SPIs quantified with ECR data:

- Overall total refers to the total number of occurrences in the ECR dataset across all types of occurrences (not limited to turbulence).
- Total or turbulence total refers to the subset of occurrences identified as relevant to this study, i.e. those involving in-flight turbulence encounters.

Flight phase and altitude

SPIs broken down by flight phase or altitude bands require normalisation by time spent at each flight phase or flight level or, alternatively, by distance flown, rather than by count of flights. Normalisation by flight count alone introduces a systematic bias, as flight time is distributed very unevenly across flight phases and altitude bands. For example, the cruise phase accounts for a disproportionate share of total flight time relative to climb and descent phases.

Route type and aircraft type

No exposure-adjusted SPIs are currently defined for route type or aircraft type segmentations. The available exposure dataset does not provide a breakdown at this level of granularity, and a suitable normalisation basis has not yet been identified. In the absence of exposure normalisation, results for these segmentations

are expressed as percentages of turbulent occurrences. It should be noted that the uneven distribution of flights across route types and aircraft types may complicate interpretation, as certain categories are structurally overrepresented in the dataset.

Turbulence events and turbulence episodes (specific to the analysis of recorded flight data)

The methodology applied to flight data produces outputs at two levels of granularity: turbulence events (single occurrence of a load factor exceedance) and turbulence episodes (groups of episodes occurring within a defined time window and attributed to the same turbulence encounter). No explicit distinction between these two levels is made within the SPI definitions. Unless otherwise stated, SPIs are computed at the episode level. Where analysis at the event level is warranted for a specific indicator, this is noted in the relevant SPI specification.

Appendix A.3 Pseudocodes for ECR SPIs

E.1.1 - Number of turbulence occurrences

COUNT (Number of turbulence occurrences)

E.1.2 - Number of turbulence occurrences as a percentage of the total ECR occurrences

COUNT (Number of turbulence occurrences)

/ Total ECR occurrences × 100

E.1.3 - Number of turbulence occurrences per 1,000 flights

COUNT (Number of turbulence occurrences)

/ Total flights × 1,000

E.2.1 - Number of turbulence occurrences by intensity level as a percentage of turbulence occurrences

COUNT (Number of turbulence occurrences)

GROUPED BY Intensity level

/ Total turbulent occurrences × 100

E.2.2 - Number of turbulence occurrences by intensity level per 1,000 flights

COUNT (Number of turbulence occurrences)

GROUPED BY Intensity level

/ Total flights × 1,000

E.3.1 - Number of turbulence occurrences by damage severity level

COUNT (Number of turbulence occurrences)

GROUPED BY Highest Damage

E.3.2 - Number of turbulence occurrences by damage severity level as a percentage of turbulence occurrences

COUNT (Number of turbulence occurrences)

GROUPED BY Highest Damage

/ Total turbulent occurrences × 100

E.4.1 - Number of turbulence occurrences by intensity level and damage severity as a percentage of turbulence occurrences

COUNT (Number of turbulence occurrences)

GROUPED BY Intensity level and Highest Damage

/ Total turbulent occurrences × 100

E.5.1 - Number of turbulence occurrences with injury as a percentage of turbulence occurrences

COUNT (Number of turbulence occurrences)

WHERE Total Injuries > 0

/ Total turbulent occurrences × 100

E.5.2 - Number of turbulence occurrences with injury per 1,000 flights

COUNT (Number of turbulence occurrences)

WHERE Total Injuries > 0

/ Total flights × 1,000

E.6.1 - Number of turbulence occurrences with injury, by injury severity level as a percentage of turbulence occurrences

COUNT (Number of turbulence occurrences)

WHERE Total Injuries > 0

GROUPED BY Injury Level

/ Total turbulent occurrences × 100

E.6.2 - Number of turbulence occurrences with injury, by injury severity level per 1,000 flights

COUNT (Number of turbulence occurrences)

WHERE Total Injuries > 0

GROUPED BY Injury Level

/ Total flights × 1,000

E.7.1 - Number of turbulence occurrences with injury, by turbulence intensity and injury severity level as a percentage of turbulence occurrences

COUNT (Number of turbulence occurrences)

WHERE Total Injuries > 0

GROUPED BY Intensity level and Injury Level

/ Total turbulent occurrences × 100

E.8.1 - Distribution of turbulence related injuries amongst passengers, flight crew, and cabin crew, as a percentage of turbulence occurrences

COUNT (Number of turbulence-related injuries)

GROUPED BY Injured Person Type

WHERE Injured Person Type is one of:

- * Passenger
- * Flight Crew
- * Cabin Crew

/ Total turbulent occurrences × 100

E.8.2 - Distribution of turbulence related injuries amongst passengers, flight crew, and cabin crew, per 1,000 flights

COUNT (Number of turbulence-related injuries)

GROUPED BY Injured Person Type

WHERE Injured Person Type is one of:

- * Passenger
- * Flight Crew
- * Cabin Crew

/ Total flights × 1,000

E.9.1 - Number of turbulence occurrences with injury among pilots, cabin crew, passengers by severity as a percentage of turbulence occurrences

COUNT (Number of turbulence-related injuries)

GROUPED BY Injured Person Type and Severity Level

WHERE Injured Person Type is one of:

- * Passenger
- * Flight Crew
- * Cabin Crew

/ Total flights × 1,000

E.10.1 - Distribution of turbulence related injuries per location inside the aircraft as a percentage of turbulence occurrences

COUNT (Number of turbulence-related injuries)

GROUPED BY Injury Location within Aircraft

/ Total turbulent occurrences × 100

E.11.1 - Number of turbulence occurrences with injury per location inside the aircraft by severity as a percentage of turbulence occurrences

COUNT (Number of turbulence-related injuries)

GROUPED BY Injury Location within Aircraft and Severity Level

/ Total turbulent occurrences × 100

E.12.1 - Distribution of turbulence related injuries per activity inside the aircraft as a percentage of turbulence occurrences

COUNT (Number of turbulence-related injuries)

GROUPED BY Activity During Injury

/ Total turbulent occurrences × 100

E.13.1 - Number of turbulence occurrences with injury per activity inside the aircraft by severity as a percentage of turbulence occurrences

COUNT (Number of turbulence-related injuries)
GROUPED BY Activity During Injury and Severity Level
/ Total turbulent occurrences × 100

E.14.1 - Number of turbulence occurrences by turbulence type as percentage of turbulence occurrences

COUNT (Number of turbulence occurrences)
GROUPED BY Turbulence Type
/ Total turbulent occurrences × 100

E.15.1 - Number of turbulence occurrences with injury by turbulence type as a percentage of turbulence occurrences with injury

COUNT (Number of turbulence occurrences)
WHERE Total Injuries > 0
GROUPED BY Turbulence Type
/ Total turbulent occurrences with injury × 100

E.16.1 - Number of turbulence occurrences with injury by turbulence type and injury severity level as a percentage of turbulence occurrences with injury

COUNT (Number of turbulence occurrences)
WHERE Total Injuries > 0
GROUPED BY Turbulence Type and Injury Level
/ Total turbulent occurrences with injury × 100

E.17.1 - Number of turbulence occurrences by turbulence type and intensity level as a percentage of turbulence occurrences

COUNT (Number of turbulence occurrences)
GROUPED BY Turbulence Type and Intensity Level
/ Total turbulent occurrences × 100

E.18.1 - Number of turbulence occurrences by altitude (FL) as a percentage of turbulence occurrences

COUNT (Number of turbulence occurrences)
GROUPED BY Altitude (Flight Level Band)
/ Total turbulent occurrences × 100

E.19.1 - Number of turbulence occurrences by altitude (FL) and intensity level as a percentage of turbulence occurrences

COUNT (Number of turbulence occurrences)

GROUPED BY Altitude (Flight Level Band) and Intensity level
/ Total turbulent occurrences $\times 100$

E.20.1 - Number of turbulence occurrences by altitude (FL) and turbulence type as a percentage of turbulence occurrences

COUNT (Number of turbulence occurrences)
GROUPED BY Altitude (Flight Level Band) and Turbulence Type
/ Total turbulent occurrences $\times 100$

E.21.1- Number of turbulence occurrences by State Area of Occurrence as a percentage of turbulence occurrences

COUNT (Number of turbulence occurrences)
GROUPED BY State/Area of Occurrence
/ Total turbulent occurrences $\times 100$

E.21.2 - Number of turbulence occurrences by State Area of Occurrence per 1,000 flights

COUNT (Number of turbulence occurrences)
GROUPED BY State/Area of Occurrence
/ Total flights (by State/Area of Occurrence) $\times 1,000$

E.22.1 - Number of turbulence occurrences by State Area of Occurrence and turbulence type per 1,000 flights

COUNT (Number of turbulence occurrences)
GROUPED BY State/Area of Occurrence and Turbulence Type
/ Total flights (by State/Area of Occurrence) $\times 1,000$

E.23.1 - Number of turbulence occurrences by flight phase as a percentage of turbulence occurrences

COUNT (Number of turbulence occurrences)
GROUPED BY Flight Phase
/ Total turbulent occurrences $\times 100$

E.24.1 - Number of turbulence occurrences by flight phase and turbulence intensity as a percentage of turbulence occurrences

COUNT (Number of turbulence occurrences)
GROUPED BY Flight Phase and Intensity level
/ Total turbulent occurrences $\times 100$

E.25.1 - Number of turbulence occurrences with injuries by flight phase as a percentage of turbulence occurrences

COUNT (Number of turbulence occurrences)
WHERE Total Injuries > 0
GROUPED BY Flight Phase
/ Total turbulent occurrences × 100

E.26.1 - Number of turbulence occurrences by flight phase and turbulence type as a percentage of turbulence occurrences

COUNT (Number of turbulence occurrences)
GROUPED BY Flight Phase and Turbulence Type
/ Total turbulent occurrences × 100

E.27.1 - Number of turbulence occurrences for short vs. long haul routes as percentage of turbulence occurrences

COUNT (Number of turbulence occurrences)
GROUPED BY Route Haul Type
WHERE Route Haul Type is one of:
 * Short haul
 * Long haul
/ Total turbulent occurrences × 100

E.28.1 - Number of turbulence occurrences for short vs. long-haul routes by turbulence intensity as percentage of turbulence occurrences

COUNT (Number of turbulence occurrences)
GROUPED BY Route Haul Type and Intensity Level
WHERE Route Haul Type is one of:
 * Short haul
 * Long haul
/ Total turbulent occurrences × 100

E.30.1 - Seasonality of number of turbulence occurrences per 1,000 flights

COUNT (Number of turbulence occurrences)
GROUPED BY Month
/ Total flights (by Month) × 1,000

E.31.1 - Seasonality of number of turbulence occurrences with injuries per 1,000 flights

COUNT (Number of turbulence occurrences)
WHERE Total Injuries > 0
GROUPED BY Month
/ Total flights (by Month) × 1,000

E.32.1 - Seasonality of number of turbulence occurrences by turbulence type per 1,000 flights

COUNT (Number of turbulence occurrences)
GROUPED BY Month and Turbulence Type
/ Total flights (by Month) × 1,000

E.33.1 - Number of overspeed events during/due to turbulence as a percentage of turbulence occurrences

COUNT (Number of turbulence occurrences)
WHERE Event Type = "Overspeed"
/ Total turbulent occurrences × 100

E.34.1 - Number of aircraft upset during/due to turbulence as a percentage of turbulence occurrences

COUNT (Number of turbulence occurrences)
WHERE Event Type = "Aircraft Upset"
/ Total turbulent occurrences × 100

E.35.1 - Number of level bust during/due to turbulence as a percentage of turbulence occurrences

COUNT (Number of turbulence occurrences)
WHERE Event Type = "Level Bust"
/ Total turbulent occurrences × 100

E.36.1 - Number of injured person on board during/due to turbulence as a percentage of turbulence occurrences

COUNT (Number of turbulence occurrences)
WHERE Event Type = "Injured Person"
/ Total turbulent occurrences × 100

E.37.1 - Number of aircraft damaged during/due to turbulence as a percentage of turbulence occurrences

COUNT (Number of turbulence occurrences)
WHERE Event Type = "Aircraft Damaged"
/ Total turbulent occurrences × 100

E.38.1 - Number of aircraft damaged due to dynamic g-loads during/due to turbulence as a percentage of turbulence occurrences

COUNT (Number of turbulence occurrences)
WHERE Event Type = "Aircraft Damaged due to dynamic g-loads"
/ Total turbulent occurrences × 100

E.39.1 - Number of loss of separation during/due to turbulence as a percentage of turbulence occurrences

COUNT (Number of turbulence occurrences)

WHERE Event Type = "Loss of Separation"

/ Total turbulent occurrences × 100

E.40.1 - Number of reduction in safety margins during/due to turbulence as a percentage of turbulence occurrences

COUNT (Number of turbulence occurrences)

WHERE Event Type = "Reduction in Safety Margins"

/ Total turbulent occurrences × 100

E.41.1 - Number of operational consequences during/due to turbulence as a percentage of turbulence occurrences

COUNT (Number of turbulence occurrences)

WHERE Event Type = "Operational Consequences"

/ Total turbulent occurrences × 100

Appendix B DETAILED ECR PROCESSING LOGIC

The scope defined in Section 3.2 was converted into a set of filtering criteria applied to the ECR occurrence database in order to obtain the initial dataset for the turbulence event identification process. The specific filtering criteria used are shown below.

```
Occurrence "UTC Date" value is between [2015 – 2025]
AND
Aircraft satisfies the definition of Commercial Air Transport (CAT) – Complex Aircraft, where:
    Aircraft "Operation Type" value is Commercial Air Transport
    AND
    (
        Aircraft "Aircraft Category" value is Large Aeroplane
        OR
        (
            Aircraft "Maximum Take Off Mass" is greater than 5700 kg
            OR
            Aircraft "Mass Group" is equal to:
                ▪ > 272 000 kg
                ▪ 27 001 – 272 000 kg
                ▪ 5 701 kg – 27 000 kg
            OR
            Aircraft "Propulsion Type" is equal to Turbofan
            Aircraft "Number of Engines" is equal or greater than 1
            OR
            Aircraft "Propulsion Type" is equal to Turboprop
            Aircraft "Number of Engines" is equal or greater than 2
        )
    )
AND
Occurrence "Detection Phase" value is equal to:
    ▪ Initial Climb
    ▪ Climb
    ▪ En-route
    ▪ Descent
    ▪ Approach
    ▪ Null
    ▪ Unknown
```

An ECR occurrence was considered a candidate for the study if it was directly related to a turbulence encounter consistent with the scope defined in Section 3.2. The exact logic used to detect such occurrences ensures the relevant taxonomy values associated with in-flight turbulence encounters were found according to the query logic shown in the box below. Refer to Section 4.1.2 for further details.

Occurrence "*Occurrence Category*" value has:

- TURB: Turbulence Encounter

OR

Events "*Event Type – Level 4*" value is equal to:

- Turbulence Encounter
- Turbulence Damage
- Injuries due to Turbulence

OR

Risk Assessment "*Key Risk Area – Level 2*" value is equal to:

- Other Injuries - Turbulence

OR

Events "*Descr factor subject – Level 4*" value is equal to:

- Clear-air Turbulence
- Turbulence in Cloud
- Other wind/Turbulence
- Terrain Induced Turbulence

Appendix C ADDITIONAL ANALYSIS OF RECORDED FLIGHT DATA

This appendix provides additional figures and analysis of the recorded flight data sample to complement the characterisation of turbulence encounters and the main findings presented in Chapter 5. Appendix C.1 presents additional information regarding the physical structure of turbulence episodes based on recorded flight data discussed in Section 5.2.3, while Appendix C.2 presents additional information on the temporal distribution of turbulence episodes within flight phases presented in Section 5.3.3.

Appendix C.1 Physical structure of turbulence episodes

The analysis of the physical structure of turbulence episodes based on recorded flight data is presented in Section 5.2.3. Additional details are provided here related to the variation of the key parameters with respect to intensity level and flight phase, namely episode duration, behaviour of the N_z signal, and number of events and oscillations per episode.

Figure 93 shows the probability density function of episode duration by flight phase. All phases exhibit similar distributions, with a clear peak at approximately 15 seconds. However, differences in their spread are significant, with those phases that having longer tails in the distribution (primarily cruise and descent) leading to higher mean values. The consistency of the peak indicates that the typical temporal structure of a turbulence encounter is largely independent of the flight phase in which it occurs; what varies between phases is the likelihood of prolonged encounters.

The gap between the peak at approximately 15 seconds and the average episode duration of approximately one minute reported in Section 5.2.3 confirms that the duration distribution is strongly right-skewed. The average episode duration therefore overstates the duration of a typical episode, and both measures should be considered when assessing episode duration.

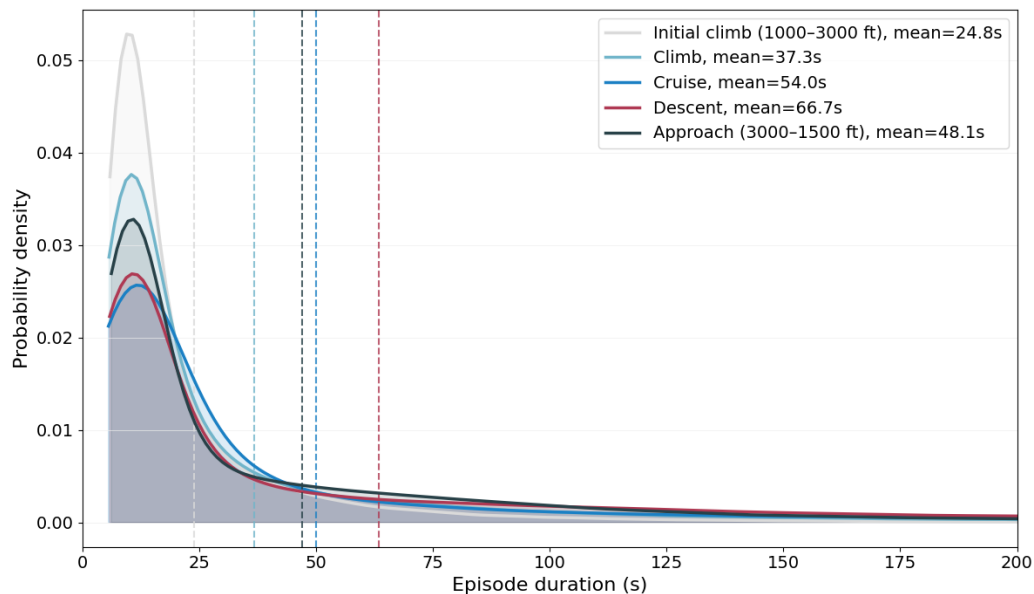


Figure 93 - Probability density of episode duration by flight phase

The behaviour of the Nz signal is characterised by its range (difference between the maximum and minimum value) and by its minimum, maximum and average values, first by intensity level (Figure 94, Figure 96, and Figure 97) and then by flight phase (Figure 95, Figure 98, and Figure 99).

By intensity level, both the central magnitude and the dispersion of Nz range increases from light to severe (Figure 94). The average Nz stays centred on zero at every intensity level, while its dispersion still widens with intensity (Figure 96, Figure 97). None of this is an independent property of the episodes. Intensity is defined on the magnitude of the Nz signal, so these distributions represent the identification and classification methodology rather than a finding about the episodes themselves. The rise in dispersion follows directly from the intensity definitions: light and moderate are bounded within equal RMS intervals of 0.1 g (0.1 to 0.2 g and 0.2 to 0.3 g), while severe intensity is defined as more than 0.3 g without an upper limit. Therefore, the severe intensity distribution has a longer tail, which is not cut-off by interval definitions in contrast with light and moderate intensity. The symmetric maximum and minimum distributions (Figure 97) and the zero-centred average are consistent with the accelerometer bias correction and high-pass filtering applied upstream, which remove any constant component from the signal.

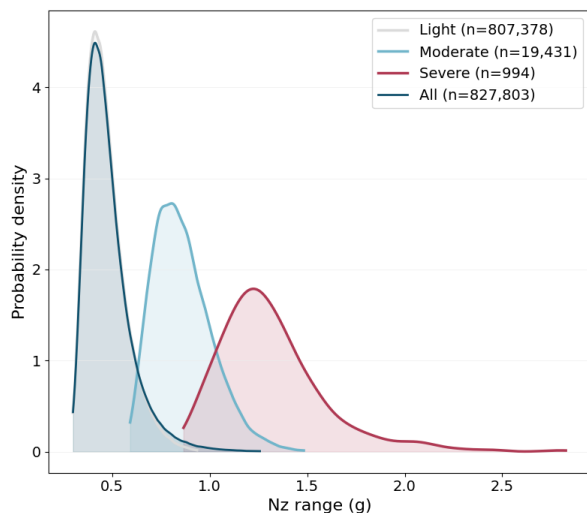


Figure 94 - Probability density of Nz range by intensity

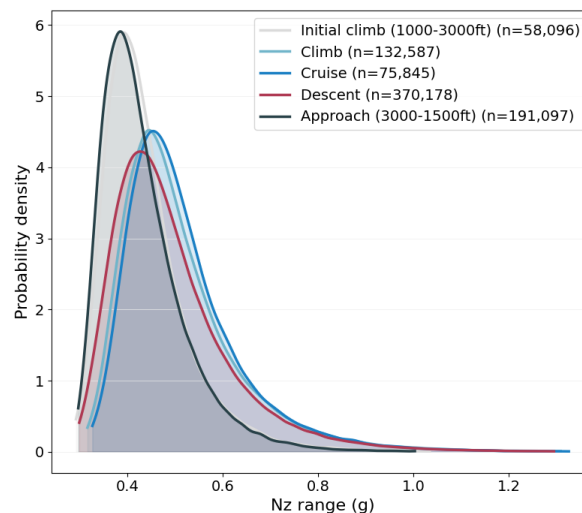


Figure 95 - Probability density of Nz range by flight phase

Examining the probability density function of the average Nz signal, range, and maximum and minimum values by flight phase, none of these quantities vary meaningfully, as seen in Figure 95, Figure 98, and Figure 99. The distributions are largely determined by the dominant intensity level within each phase, which is light intensity, so the breakdown by flight phases reproduces the light intensity distribution with only minor differences, mainly a slightly lower spread in the phases at lower altitudes. It confirms that the Nz signal values are influenced by the classification methodology and by the intensity composition of each phase, and not by any phase-specific behaviour itself.

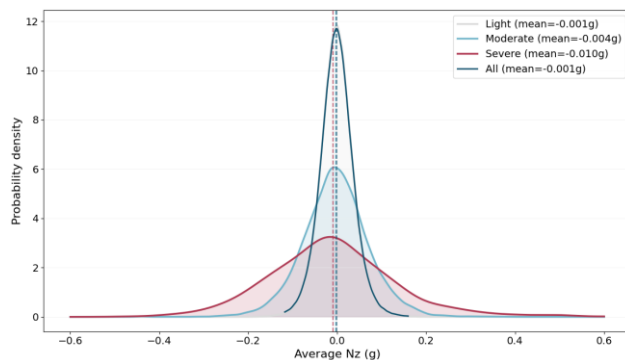


Figure 96 - Probability density of the average Nz signal value by intensity

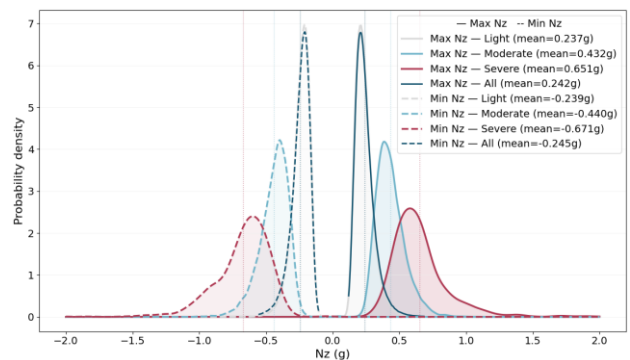


Figure 97 - Probability density of the minimum and maximum Nz signal value by intensity

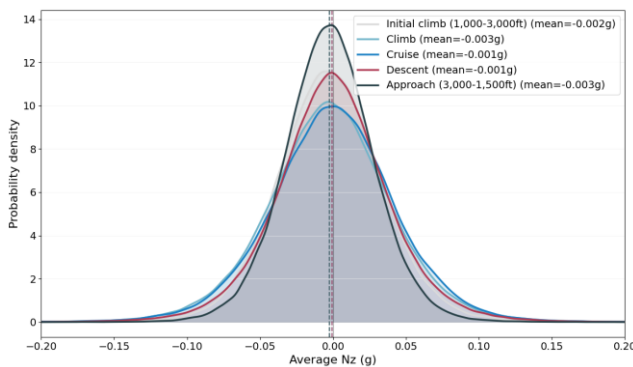


Figure 98 - Probability density of the average Nz signal value by flight phase

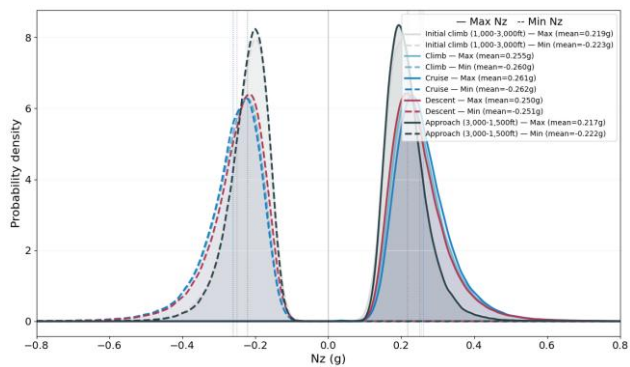


Figure 99 - Probability density of the minimum and maximum Nz signal value by flight phase

The same increase in dispersion with increasing intensity seen in Figure 94, Figure 96, and Figure 97 was observed for episode duration in Section 5.2.3. The two results are not equivalent. Intensity is defined on the basis of the Nz signal, so a widening of the Nz range distribution across intensity levels is at least partly inherent to the classification. Episode duration, by contrast, plays no part in the intensity definition. The corresponding increase in episode duration dispersion is therefore an independent characteristic of the identified episodes rather than a property of the definition. Both results indicate that higher intensity episodes constitute a less homogeneous population than light intensity episodes.

Figure 98 shows the probability density of the average Nz value by flight phase, while Figure 99 shows the maximum and minimum Nz signal values by flight phase. Both these values do not vary significantly across flight phases, although the phases at lower altitudes (initial climb and approach) exhibit a lower mean and a lower standard deviation than climb, cruise and descent.

Figure 100 shows the variation of the average number of oscillations per episode by intensity level, which increases with increasing intensity. Moderate and severe episodes contain significantly more oscillations than light ones, consistent with the increase in episode duration and number of events per episode presented in Section 5.2.3.

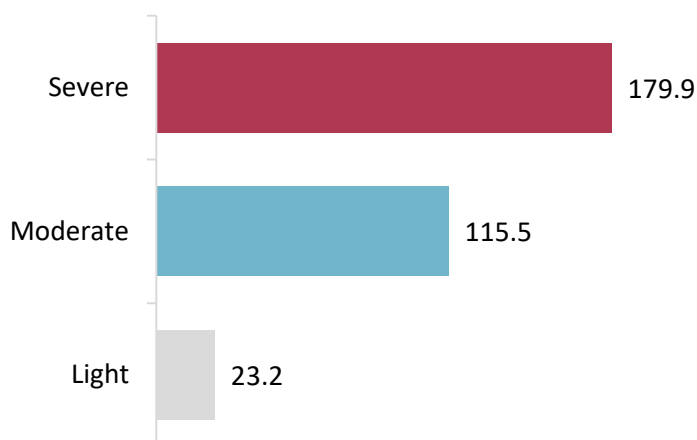


Figure 100 - Average number of oscillations per episode by intensity

Figure 101 shows the average number of turbulence events per turbulence episode by flight phase. The average values range from 1.68 in initial climb to 2.64 in descent, against an average of 2.4 events per episode across all flight phases.

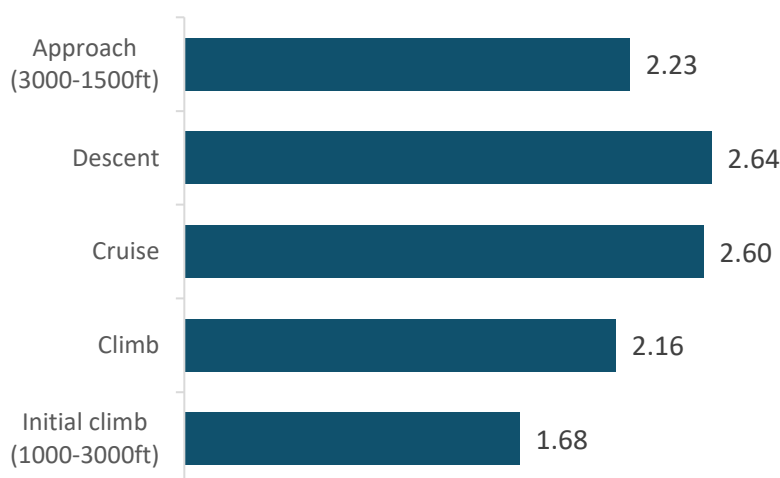


Figure 101 - Average number of events per episode by flight phase

In ascending order of average number of turbulence events per episodes, the phases are initial climb (1.68), climb (2.16), approach (2.23), cruise (2.60) and descent (2.64), with cruise and descent having effectively equivalent averages. This ordering reproduces exactly the ordering of the flight phases by mean episode duration reported in Section 5.3, where the mean duration increased from initial climb through climb and approach to descent and cruise, with the latter two having almost identical average duration. The agreement between the two orderings indicates that the variation in the number of events per episode across flight phases is associated with the corresponding variation in episode duration. The rate at which

events occur within an episode therefore appears to be approximately constant across flight phases, in the same way that it was found to be approximately constant across intensity levels.

Figure 102 shows the same breakdown with the addition of the intensity dimension, with moderate and severe episodes grouped together. The average for each phase remains very close to the corresponding light intensity value, as expected given the dominance of light episodes in the sample. Within each intensity group the ordering of the flight phases is similar: initial climb yields the lowest number of events per episode and cruise and descent the highest, for light episodes (1.66 to 2.50) as well as for moderate and severe ones (3.84 to 7.91). The phase-related variation in average number of turbulence events per episode is therefore not an artefact of a differing intensity composition between phases; rather, it persists within each intensity group.

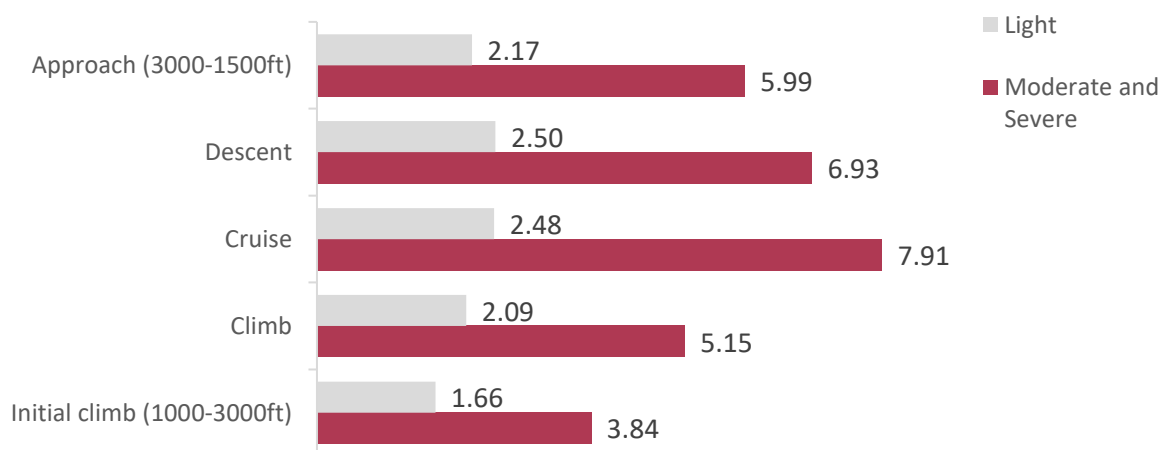


Figure 102 - Average number of events per episode by flight phase and intensity

Moderate and severe episodes contain approximately two to three times as many events as light episodes in every flight phase, consistent with the threefold difference in episode duration established earlier. Within the moderate and severe group, the highest number of events per episode occurs during cruise. Light episodes show a marginally different pattern, with the maximum in descent and cruise very close in second place.

Appendix C.2 Temporal distribution within flight phases

The analysis of the distribution of turbulence episodes within each flight phase in the recorded flight data is presented in Section 5.3.3. Additional details are provided here related to the definition of phase progress, the interpretation of the figures, and the breakdown of the distributions by intensity level.

Appendix C.2.1 Definition of phase progress

For every identified turbulence episode, its time of occurrences within the flight phase in which it occurs is expressed as the phase progress, defined as the time elapsed between the start of the phase and the

episode, divided by the total duration of that phase, and expressed as a percentage. A phase progress of 0% corresponds to the start of the phase and 100% to its end.

Phase progress is computed individually for each episode, using the phase duration of the flight in which the episode was detected rather than an average across all flights. This is necessary because phase durations vary substantially between flights, most notably between short-haul and long-haul operations, so using an absolute time reference would not be feasible across the dataset.

For the same reason, phase progress is referenced to the phase rather than to total flight time. The share of total flight time accounted for by each phase depends on sector length, i.e. the duration of the individual flight between its departure and destination airports. Therefore, a given percentage of total flight time would correspond to different points within the flight phases for flights of different sector lengths.

Appendix C.2.2 Interpretation of the figures

The figures shown in Section 5.3.3 and in this section present the probability density of turbulence episodes with respect to phase progress, with the five flight phases arranged in chronological order along the horizontal axis, each spanning 0% to 100%. The figure should be interpreted as five separate distributions placed side by side rather than as a single continuous distribution across the flight.

The interpretation rests on two key points. First, each phase is normalised independently, so each density is scaled such that the total area under its curve equals one within that phase. Density values are therefore comparable within each flight phase but not between flight phases, and the height of a curve in one phase carries no information about the exposure in that phase relative to another. Second, the horizontal axis is not a uniform time axis: equal horizontal distances correspond to different absolute durations depending on the phase and on the individual flight.

Appendix C.2.3 Breakdown by intensity level

Figure 103 and Figure 104 show the phase-progress distributions for moderate and severe episodes respectively. The distribution for light intensity turbulence episodes is not reproduced, as it is similar to the aggregated distribution shown in Section 5.3.3 almost exactly, consistent with the overwhelming dominance of light episodes in the recorded flight data.

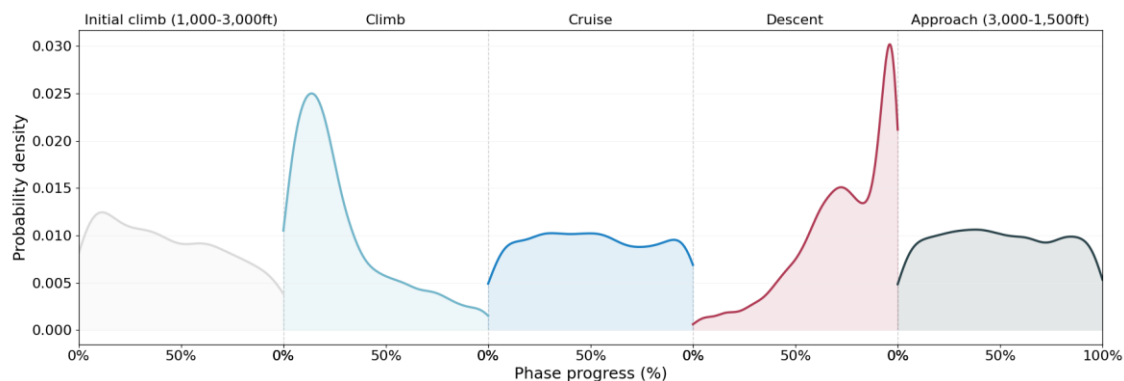


Figure 103 - Probability density of turbulence episodes of moderate intensity with respect to phase progress, by flight phase

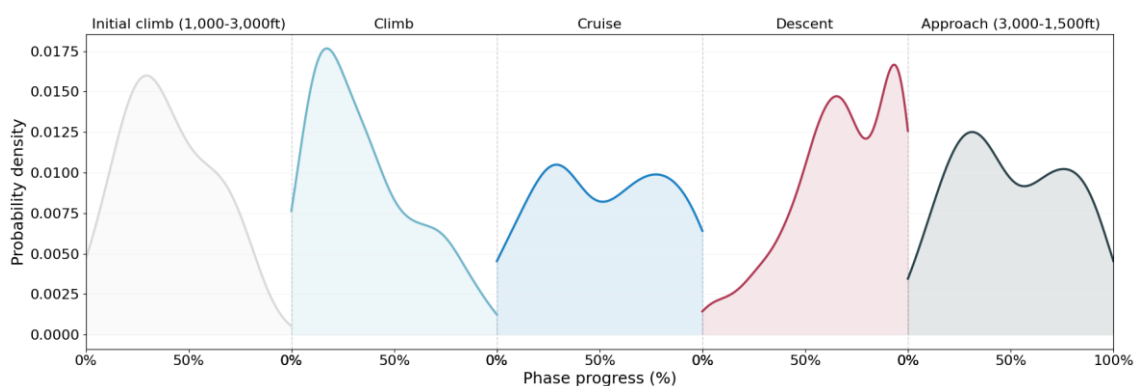


Figure 104 - Probability density of turbulence episodes of severe intensity with respect to phase progress, by flight phase

The moderate and severe distributions depart from the aggregated pattern in the two phases where that pattern is most pronounced, namely cruise and descent.

In cruise, the flat distribution seen for the aggregated data (see Figure 36) is not preserved for moderate and severe turbulence. Both moderate and severe episodes are more evenly spread across the phase, with the severe distribution showing a broad, low double hump rather than the sharp late-cruise peak of the aggregated figure. The pronounced peak at the end of cruise, which is the principal feature of the aggregated distribution, is therefore largely a feature of the light intensity episodes. This finding can also be observed in the moderate intensity episodes, but it is not clearly present in the severe intensity distribution.

In descent, the skew towards lower altitudes is preserved at all intensities: moderate and severe episodes, like light ones, are concentrated in the later part of the phase. At higher intensity this concentration is more pronounced. Rather than a smooth rise towards the end of the phase, the moderate and severe descent distributions show a distinct peak at around 60% of the phase, and this peak becomes more pronounced as intensity increases.

This feature appears to correspond to the plateau in the moderate and severe altitude distributions (see Figure 34), where episode density remains relatively high across a band of intermediate altitudes before falling away above it. One reading is that the peak marks the point in the descent at which the aircraft enters that altitude band, in which moderate and severe episodes are proportionally more frequent, which would also account for the feature strengthening with intensity. This is a hypothesis that needs verification in future research and should not be considered as a confirmed finding. One could analyse the altitude data during descent phases and see if the highest point aligns with the plateau band, which is suggested as a direction for future study.

The consistent finding across intensities is the skew towards lower altitudes in the climb and descent phases, present for light, moderate and severe episodes alike, which reinforces the altitude result presented in Section 5.2.3. The late-cruise peak behaves differently. It is most pronounced in the light intensity episodes that dominates the aggregated figure, while it remains discernible at moderate intensity, and is effectively absent at severe intensity.

Appendix D **ADDITIONAL ANALYSIS OF CONSEQUENTIAL EVENTS AND SAFETY BARRIERS PERFORMANCE**

This appendix supplements Chapter 6 with additional figures, tables and descriptions to further analyse the consequential events of turbulence encounters, as well as to enhance the explanation and results regarding the bow tie model designed and the safety barriers analysis.

Appendix D.1 **Operational consequences of turbulence-related ECR occurrences**

The operational consequences (Figure 105) provide additional information on how turbulence affected the continuation of the flight. Weather-related diversion was the most common individual operational response, followed by aircraft return, unstable approach, missed approach and en-route clearance deviation. Go-arounds and landings following an unstable approach were also identified, together with less frequent altitude, routing and airspace deviations. The results show that the operational effect of

turbulence is not limited to the moment of encounter; it may continue into subsequent flight-phase decisions and generate disruption even where no damage or serious injury is reported.

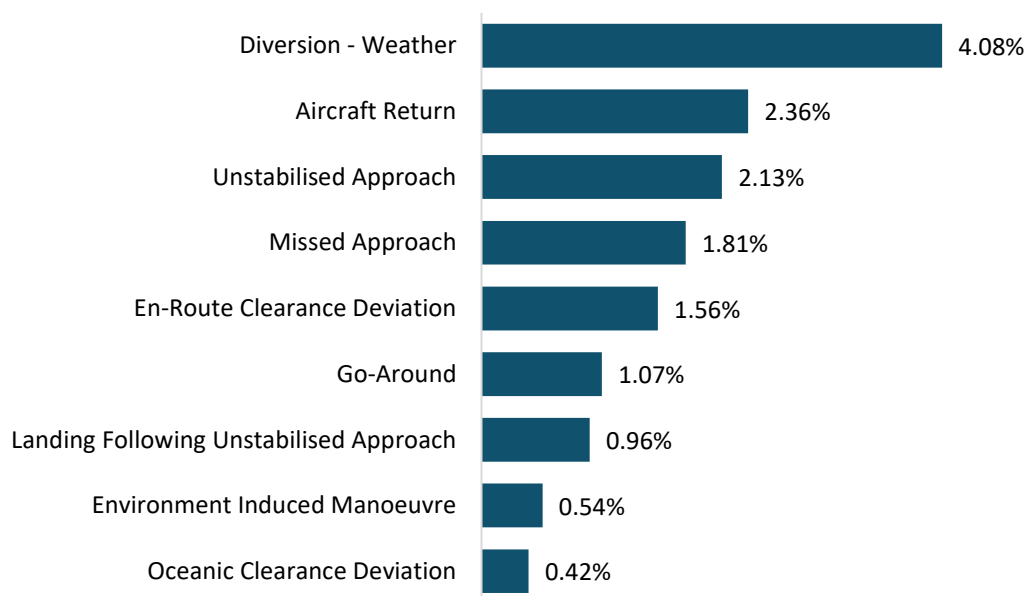


Figure 105 - Operational consequences identified through ECR

Appendix D.2 Additional analysis of consequential events in the recorded flight data

This appendix supplements Chapter 6.2.2 with figures that are not reproduced in the main text. It presents absolute event counts alongside normalised rates and then adds detail on recurrence, airspeed distributions and flight phase.

Appendix D.2.1 Autopilot disengagement

A total of 20,625 autopilot disengagements events were identified during turbulence episodes. As with the overspeed and aircraft upset analysis, the absolute number of disengagements is dominated by light turbulence (Figure 106), reflecting the much larger number of light turbulence episodes in the dataset.

A different picture emerges when the results are normalised by the total number of turbulence episodes within each intensity class (Figure 107). Under this representation, autopilot disengagements become progressively more frequent with increasing turbulence intensity, reaching 236.42 disengagements per 1,000 severe turbulence episodes. This compares with 91.55 per 1,000 episodes for moderate turbulence

and only 23.04 per 1,000 episodes for light turbulence. Consequently, an autopilot disengagement is approximately ten times more likely to occur during a severe turbulence episode than during a light one.

This trend is consistent with the increasing aircraft response associated with more intense turbulence. Larger attitude excursions, higher load factors, and airspeed variations are more likely to activate autopilot disengagement logic or prompt pilots to manually disconnect the autopilot in order to regain direct control of the aircraft.

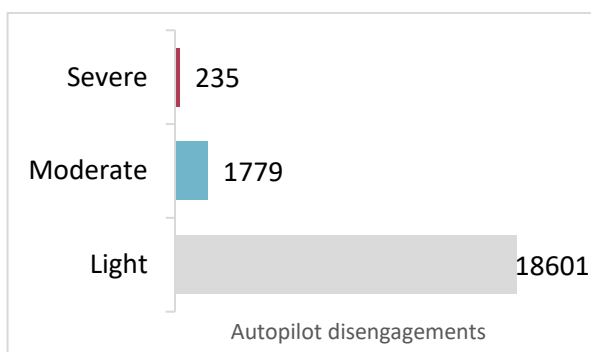


Figure 106 - Number of autopilot disengagements events by intensity

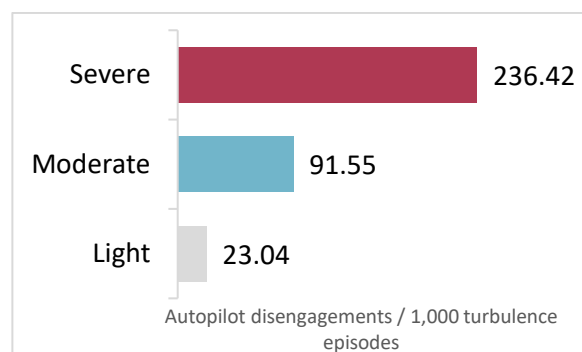


Figure 107 - Number of autopilot disengagements events by intensity, normalised by 1,000 turbulence episodes. Normalisation is based on total number of turbulence episodes within each intensity

Figure 108 examines recurrence within episodes that contain at least one autopilot disengagement. The mean rises only slightly with intensity, from 1.27 for light to 1.32 for moderate and 1.34 for severe turbulence. The stronger change is therefore in the likelihood of a disengagement occurring, rather than in the number of repeated disengagements within an affected episode.

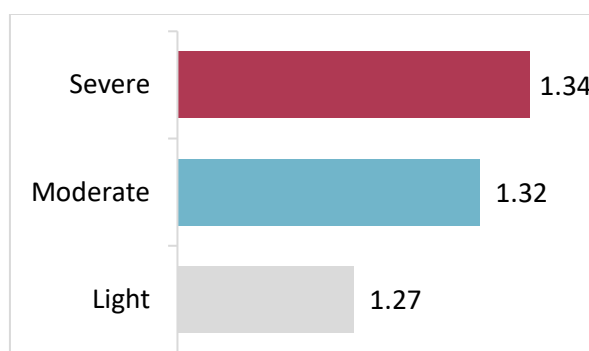


Figure 108 - Average number of autopilot disengagements by intensity

Appendix D.2.2 Overspeed

A total of 899 events were identified as a consequence of turbulence. Figure 109 presents the absolute number of overspeed events by turbulence intensity. As expected, the majority of overspeed events are associated with light turbulence, followed by moderate and severe turbulence. This reflects the underlying distribution of turbulence episodes, where light turbulence represents the vast majority of the dataset.

A different picture emerges when the results are normalised by the total number of turbulence episodes within each intensity class (Figure 110). Under this representation, overspeed events are substantially more likely to occur during severe turbulence, with a rate of 27.16 overspeed events per 1,000 severe turbulence episodes. Moderate turbulence exhibits a considerably lower rate of 7.62 events per 1,000 episodes, while light turbulence is associated with only 0.9 events per 1,000 episodes.

These results demonstrate a strong relationship between turbulence intensity and the occurrence of overspeed events. Relative to light turbulence, overspeed events are approximately 8 times more frequent during moderate turbulence and 30 times more frequent during severe turbulence. This indicates that increasing turbulence intensity is associated not only with a greater aircraft response in terms of magnitude and duration, but also with a substantially higher probability of exceeding the aircraft operating speed limits.

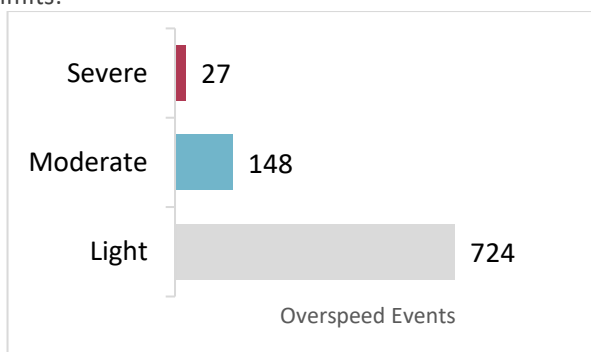


Figure 109 - Number of overspeed events by intensity

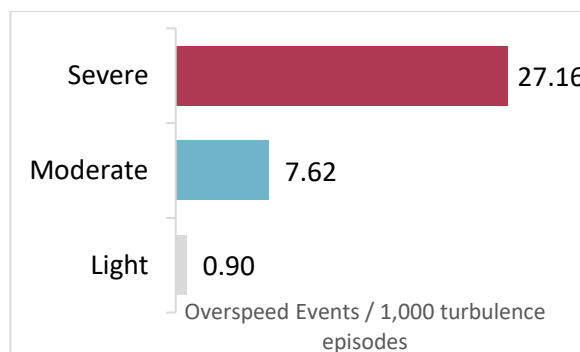


Figure 110 - Number of overspeed events by intensity, normalised by 1,000 turbulence episodes. Normalisation is based on total number of turbulence episodes within each intensity

Appendix D.2.3 Aircraft upset

A total of 47 aircraft upset events, and 199 onsets of aircraft upset events were identified during turbulence episodes. Although aircraft upset onsets do not meet the criteria to be classified as full aircraft upsets, they nevertheless represent excursions beyond the normal attitude-rate envelope and may therefore indicate the early stages of an upset or a significant aircraft response to turbulence. The considerably larger number of upset onsets compared with full upsets suggests that, in most cases, the aircraft response remains limited and does not develop into a sustained upset condition.

Figure 111 shows the number of upsets by intensity, and Figure 112 shows the rates normalised by 1,000 turbulence episodes. As observed for the other consequential events, the occurrence rate increases with turbulence intensity. Specifically, the rate increases by approximately one order of magnitude from light to moderate turbulence, and by a further factor of two from moderate to severe turbulence.

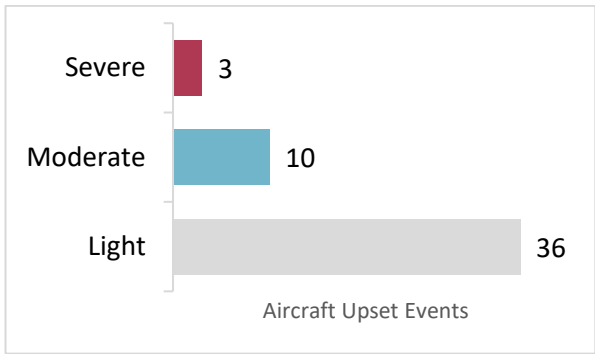


Figure 111 - Number of aircraft upset events by intensity

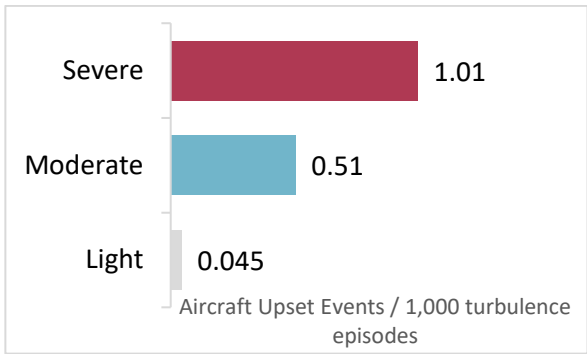


Figure 112 - Number of aircraft upset events by intensity, normalised by 1,000 turbulence episodes¹⁹

Appendix D.2.4 TCAS

Out of all turbulence episodes captured in the dataset, 14 TCAS RA were identified either during, or within 1 minute after a turbulence episode. 12 of those correspond to TCAS events within the turbulence episode itself, while the other 2 correspond to events that started within 1 minute of the turbulence episode ending. Figure 113 shows the number of TCAS events by intensity of the aircraft’s response, while Figure 114 shows the rate per 1,000 turbulence episodes within each intensity. The majority of TCAS events happen during a light turbulence. This is caused by the large number of light episodes compared to other severities. When calculating the ratio, moderate has one order of magnitude more than light turbulence Interestingly, no TCAS events were identified during severe turbulence episodes. Given the limited number of severe cruise turbulence episodes in the dataset, this result should be interpreted with caution. It also supports the hypothesis raised in 6.2.2 that the identified TCAS events are not necessarily a direct consequence of the turbulence itself, but rather the temporal coincidence of two independent phenomena.

¹⁹ Normalisation is based on total number of turbulence episodes within each intensity.

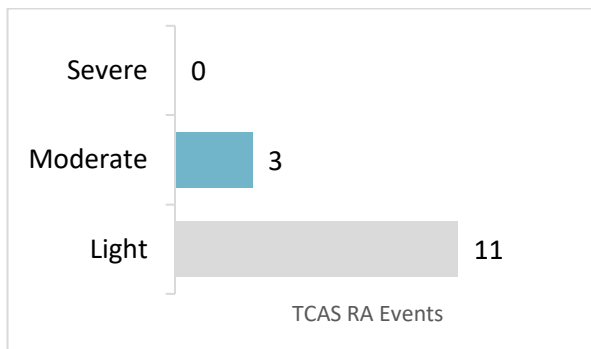


Figure 113 - Number of TCAS RA events by intensity

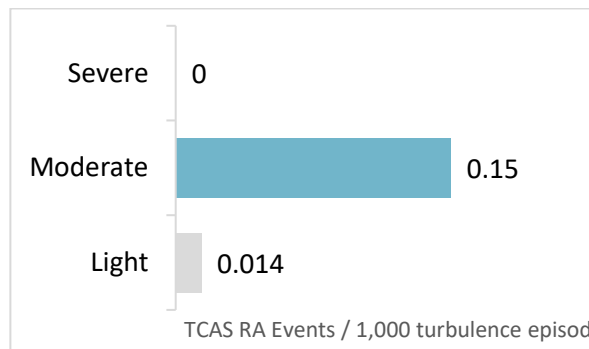


Figure 114 - Number of TCAS RA events by intensity, normalised by 1,000 turbulence episodes²⁰

Figure 115 shows the breakdown by flight phase. Descent exhibits the highest number of TCAS events, followed by climb and cruise, which is consistent with the higher traffic density typically encountered during the arrival phase. Although TCAS events are more frequently observed in the vicinity of turbulence episodes during descent, this should not be interpreted as evidence of a causal relationship. Rather, the higher co-occurrence is likely explained by the greater density of both turbulence encounters and aircraft traffic during this phase of flight, increasing the probability that the two types of events occur close together in time.

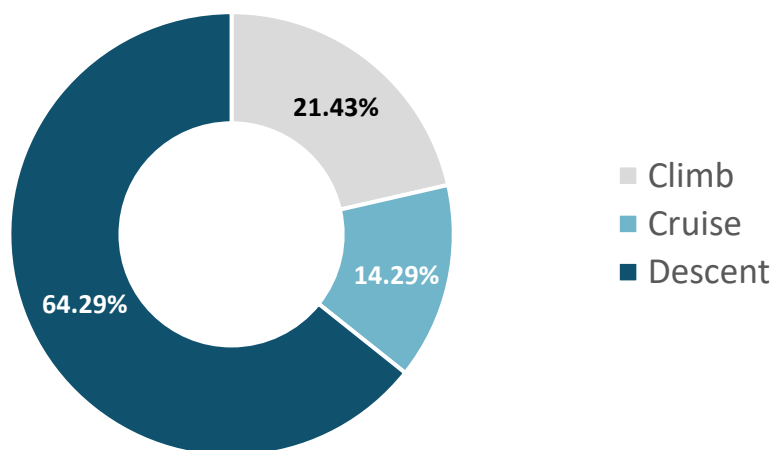


Figure 115 - Breakdown of TCAS RA events by flight phase

²⁰ Normalisation is based on total number of turbulence episodes within each intensity.

Appendix D.3 Additional safety barriers analysis

This section provides additional information regarding the barrier actions used within the bow tie model presented in Section 6.3.1, as well as a detailed analysis of each ERCS barrier type covered through the analysis, that expands the overall barrier assessment from Section 6.3.2.

Appendix D.3.1 Barrier actions identification

Combining the ALBATROS Task 2.1 bow tie model with EASA's Safety Impact Assessment Task Team on Turbulence current investigation, 37 specific barrier actions were identified in Table 16. The actions include technical capabilities and design characteristics, planning activities, operational procedures, crew monitoring and decision-making, warning-system responses and late recovery measures.

Each identified barrier is categorised within the ERCS barrier type that is being covered with the action. The position assigned to each action indicates whether its primary safety function operates before or after the turbulence encounter. The safety-function descriptions summarise the intended contribution of each action to preventing or containing escalation.

Table 16 - Barrier actions identified in turbulence-related ECR occurrences

ERCS barrier type	Position	Specific barrier action
1. Aircraft, equipment and infrastructure design	Before turbulence	Aircraft equipped with functional autopilot and autothrottle systems to maintain stable flight during turbulence
1. Aircraft, equipment and infrastructure design	Before turbulence	Aircraft equipped with secure jump seats and restraint systems for cabin crew
1. Aircraft, equipment and infrastructure design	Before turbulence	Aircraft equipped with secure storage for service equipment and loose items in the cabin
1. Aircraft, equipment and infrastructure design	Before turbulence	Onboard weather radar capability designed to detect liquid precipitation in convective cells
1. Aircraft, equipment and infrastructure design	After turbulence	Aircraft structural design certified to load-factor limits absorbed the turbulence loads
1. Aircraft, equipment and infrastructure design	After turbulence	High angle-of-attack and flight-envelope protections prevented the aircraft from exceeding its operational limits
2. Tactical planning	Before turbulence	Crew planned sufficient fuel for holding and a diversion alternate during flight preparation
2. Tactical planning	Before turbulence	Dispatch prepared a flight plan avoiding forecast turbulence
2. Tactical planning	Before turbulence	Flight crew conducted a pre-flight weather briefing addressing turbulence
2. Tactical planning	Before turbulence	Flight crew requested turbulence information from ATC before reaching cruise level
2. Tactical planning	Before turbulence	Pre-flight weather forecast and turbulence prediction
3. Regulation, procedures and processes	Before turbulence	Captain instructed cabin crew to take their seats and secure the cabin before anticipated severe turbulence

3. Regulation, procedures and processes	Before turbulence	Captain made a cabin turbulence announcement before entering forecast turbulence
3. Regulation, procedures and processes	Before turbulence	Flight crew activated the seatbelt sign in anticipation of forecast turbulence
3. Regulation, procedures and processes	Before turbulence	Flight crew communicated with cabin crew regarding the timing of service completion and cabin preparation
3. Regulation, procedures and processes	Before turbulence	SOP procedures for cabin crew meal-service timing during flights with forecast turbulence
3. Regulation, procedures and processes	Before turbulence	SOP procedures requiring cabin crew to secure all service equipment before seatbelt-sign illumination
3. Regulation, procedures and processes	Before turbulence	SOP procedures requiring flight crew to request an altitude change when turbulence is encountered or forecast, and effective performance of the action
3. Regulation, procedures and processes	Before turbulence	SOPs related to turbulence-penetration speed procedures applied during the encounter
3. Regulation, procedures and processes	Before turbulence	ATC provision of turbulence reports to the flight crew
3. Regulation, procedures and processes	After turbulence	Cabin crew adherence to procedures requiring crew to be seated and restrained when the seatbelt sign is illuminated
3. Regulation, procedures and processes	After turbulence	Flight crew decision-making regarding diversion to the nearest suitable airport versus continuation to the planned destination
3. Regulation, procedures and processes	After turbulence	Flight crew executed the QRH/SOP severe-turbulence procedure
4. Situational awareness and action	Before turbulence	Flight crew correctly interpreted weather-radar limitations
4. Situational awareness and action	Before turbulence	Flight crew monitored a live weather application during cruise to anticipate developing turbulence areas
4. Situational awareness and action	Before turbulence	Flight crew performed a visual lookout for convective weather or cumulonimbus clouds during flight
4. Situational awareness and action	Before turbulence	Flight crew used onboard weather radar to detect convective cells and select avoidance routing
4. Situational awareness and action	After turbulence	Flight crew activated the seatbelt sign immediately upon encountering unexpected turbulence
4. Situational awareness and action	After turbulence	Flight crew descended or changed level and informed ATC to exit the turbulence zone
4. Situational awareness and action	After turbulence	Flight crew monitored essential flight parameters during and after the encounter
4. Situational awareness and action	After turbulence	Successful autopilot management of the turbulence
5. Warning systems operation and action	After turbulence	Altitude-deviation or altitude-alert warning activated following an uncommanded altitude excursion
5. Warning systems operation and action	After turbulence	Autopilot-disengagement aural and visual warnings annunciated during the upset
5. Warning systems operation and action	After turbulence	Flight crew appropriately responded to overspeed aural and visual warnings
5. Warning systems operation and action	After turbulence	Stall-warning system activated

6. Late recovery from a potential accident situation	After turbulence	Crew re-engaged autopilot or autothrust and stabilised the flight path at a safe level after the excursion
6. Late recovery from a potential accident situation	After turbulence	Flight crew declared a medical emergency or PAN due to injuries and coordinated ATC priority and medical assistance

The identified actions show that the barrier system extends across the complete occurrence sequence. Before the encounter, the principal safety functions concern hazard identification, turbulence avoidance, operational preparation and reduction of occupant exposure. After the encounter, the emphasis moves towards maintaining aircraft controllability, detecting deviations, limiting the duration of exposure, reducing injury severity and recovering from unsafe aircraft states.

The allocation of an action to the before or after side should not be interpreted as indicating that its contribution is isolated to one moment. Several barriers are interdependent. For example, weather information only becomes an effective preventive barrier when it is correctly interpreted and converted into a route, altitude or cabin-preparation action. Similarly, a warning system contributes to safety only when the alert is detected, understood and followed by an appropriate response. The detailed barrier-group results should therefore be interpreted as different layers of a connected safety system rather than as completely independent defences.

Appendix D.3.2 Detailed assessment by barrier type

The following subsections examine the specific actions identified within each ERCS barrier type and their relationship with the assessed effectiveness and reported consequential events. A set of diagrams connect each reported action to its observed effectiveness. For actions classified as Stopped, the figures then show the consequential events that were nevertheless present in the same occurrence. This structure shifts the emphasis from simply counting actions to understanding what type of escalation was contained, what safety target remained exposed and why a reported consequence can coexist with a successful barrier.

Appendix D.3.1.1 Aircraft, equipment and infrastructure design

The first barrier group is classified as failed in 27% of the occurrences and as stopped in 13% (Figure 116). The high failed share is influenced by the dataset used, as the ECR represents only those turbulence occurrences containing an associated safety or operational event which request mandatory reporting to National Aviation Authorities. An upstream design defence had therefore not prevented the assessed sequence from developing, but this does not represent a general failure rate for aircraft design or equipment.

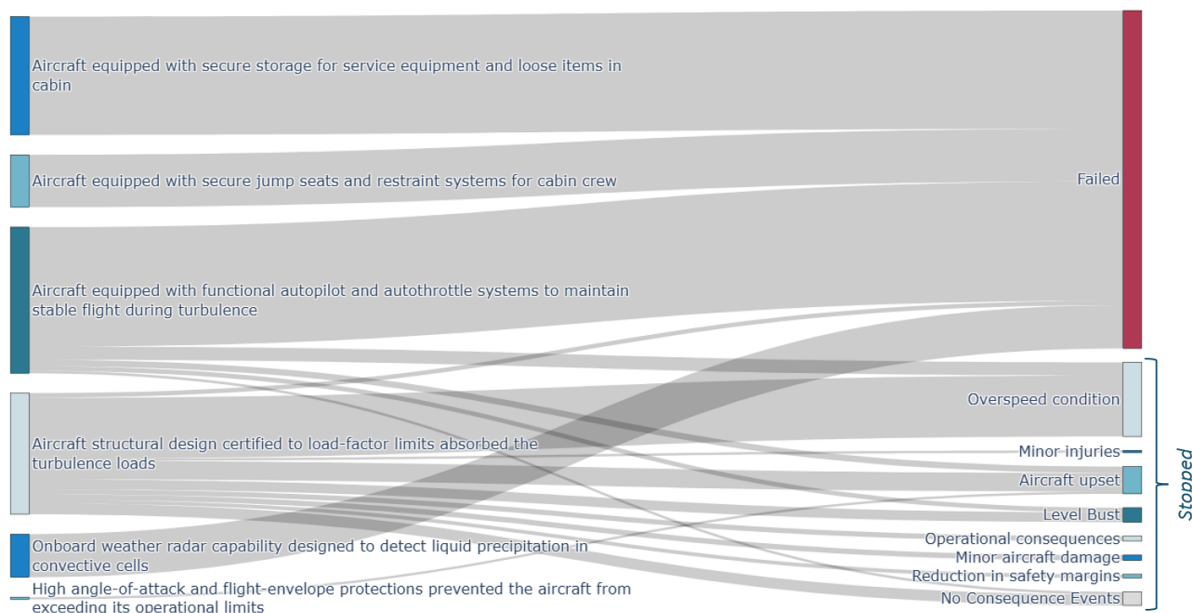


Figure 116 - Barrier type 1 actions, assessed effectiveness and linked consequential events

Occupant and cabin protection. Secure storage for service equipment and loose items, together with cabin-crew jump seats and restraint systems, is intended to reduce impact and projectile exposure in the cabin. Their failed flows are therefore most relevant to the injury pathway: the protection was not shown to have prevented continued exposure of cabin crew or passengers to abrupt motion or unsecured equipment. The narratives do not consistently establish whether the equipment was unavailable, was not used, could not be reached in time or was overcome by an abrupt encounter, so the result should not be read as a technical failure rate.

Aircraft integrity and controllability. Structural load capability, flight-envelope and angle-of-attack protection, and autopilot or autothrottle functions address a different target. They aim to keep loads, attitude, speed and flight path within survivable limits. These actions are more visible in the stopped pathways, especially structural load absorption. Their effectiveness can therefore coexist with an overspeed, upset or level bust: the intermediate deviation may occur while the barrier prevents progression towards structural failure, loss of control or another high-severity outcome.

Hazard avoidance. Onboard weather radar supports avoidance of liquid precipitation in convective cells rather than acting as a general detector of every turbulence type. A failed radar-related action in this dataset means that avoidance did not prevent the assessed reportable sequence; it does not demonstrate that the radar malfunctioned. This distinction is particularly relevant because clear-air turbulence is prominent in the characterisation and successful avoidance would normally leave no turbulence occurrence to analyse.

Among the stopped actions, overspeed is the most visible remaining aircraft-state consequence, with smaller flows to aircraft upset, level bust, operational consequences, minor damage and reductions in safety margins. Minor injuries are also present. This profile supports a severity-limiting interpretation: the design layer often protects aircraft integrity after the aircraft has already departed from the desired state, but it does not necessarily protect an unrestrained occupant. The coexistence of limited aircraft damage and occupant injury is therefore not contradictory; it reflects two different safety pathways and two different protection objectives.

Appendix D.3.1.2 Tactical planning

Tactical planning is predominantly classified as failed (65%), while 1.8 % of the occurrences show this group as the stopping barrier (Figure 117). Unlike design, planning is principally an exposure-control layer: it is intended to avoid forecast turbulence, reduce the time spent in it or preserve safe alternatives before the encounter develops. Its high failed share therefore indicates that the analysed sequence was not avoided by the available pre-flight and dispatch defences, not that the planning system caused the later consequences.

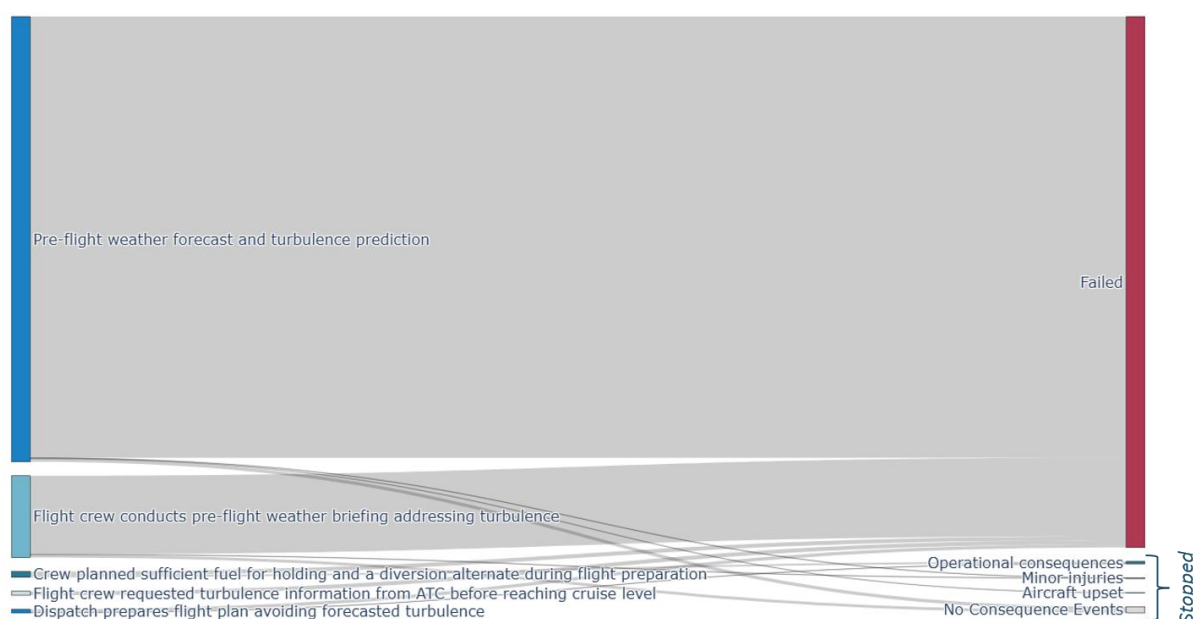


Figure 117 - Barrier type 2 actions, assessed effectiveness and linked consequential events

Anticipation and avoidance. Weather forecasting, turbulence prediction, pre-flight briefing, ATC information and dispatch routing are all intended to provide an actionable picture before exposure. The dominant failed flow concerns pre-flight weather forecast and turbulence prediction. In an occurrence dataset built around actual encounters, this is an expected selection effect: fully successful avoidance is unlikely to be reported. The result also cannot distinguish between a forecast that was inaccurate or insufficiently specific and information that was available but could not be converted into an effective route change.

Operational resilience. Fuel planning for holding, diversion or an alternate airport has a different function. It does not prevent turbulence directly; it preserves safe options when conditions require rerouting or recovery. Its value is therefore better judged by whether the crew retained a safe operational response than by whether the encounter occurred.

The small stopped subset is analytically informative. Most of its flow ends in No Consequence Events, followed by operational consequences, with only minor links to injury or aircraft upset. This is the consequence profile expected from an effective upstream barrier: either the hazardous exposure is avoided without a safety consequence, or the visible result is a route, altitude, holding or diversion decision. Such operational disruption can be the cost of risk reduction and should not automatically be interpreted as barrier failure.

The characterisation results in Section 5.6 help explain why this group is rarely identified as the final stopping layer. Clear-air turbulence represents the large majority of the classified turbulence types, and cruise flight is the most frequent phase. This combination is consistent with encounters for which the opportunity for complete pre-flight or tactical avoidance may be limited and the event must instead be managed in flight. Consequently, the broad range of downstream consequences after a planning failure reflects exposure of the whole remaining barrier system; it should not be interpreted as evidence that planning caused those consequences.

Appendix D.3.1.3 Regulations, procedures and processes

Regulations, procedures and processes provide the strongest evidence of an active stopping layer in the dataset. This group stopped escalation in 54% of the occurrences, compared with 24% classified as failed (Figure 118). The action-level evidence is important because this group contains both cabin-protection procedures and aircraft-management procedures. It is therefore the layer most capable of addressing the two principal turbulence pathways at the same time, even though no single procedure covers both completely.

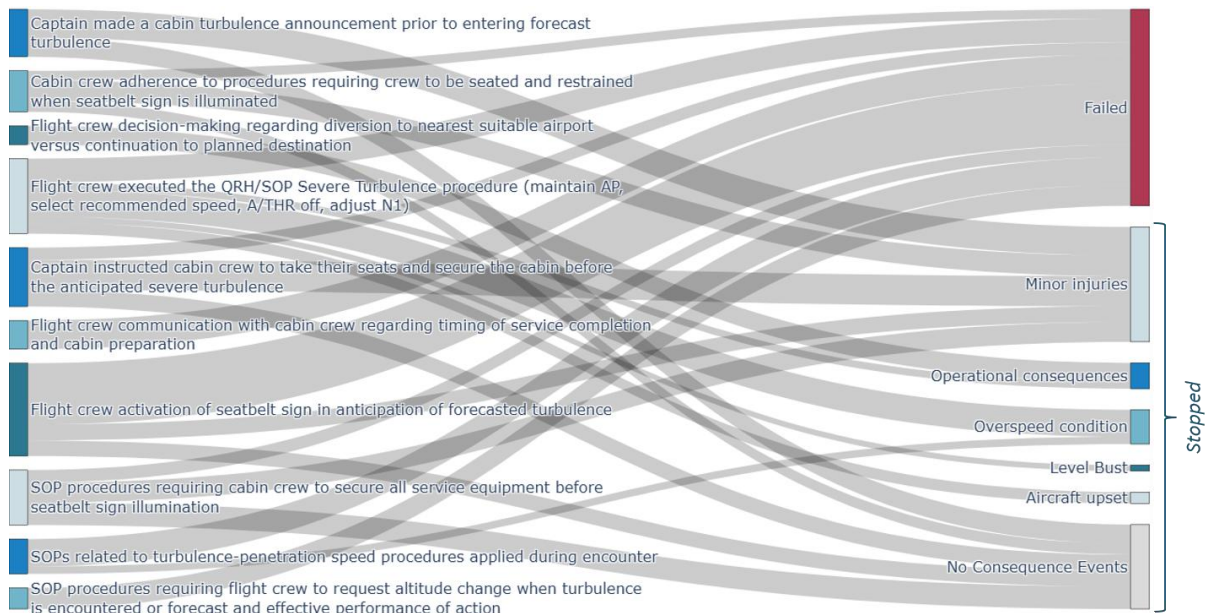


Figure 118 - Barrier type 3 actions, assessed effectiveness and linked consequential events

Protection of passengers and cabin crew. Cabin announcements, activation of the seatbelt sign, instructions to be seated and restrained, suspension or completion of service, securing of equipment and flight-deck-cabin communication all reduce occupant exposure. Where these actions are assessed as failed, the direct safety concern is injury rather than aircraft integrity. This is consistent with the characterisation, in which cabin service, aisle or galley activity and passenger or cabin-crew exposure recur among injury occurrences. The figure does not prove that a procedure was absent; it may have been late, incompletely followed or insufficient for the timing and intensity of the encounter.

Protection of the aircraft state and flight path. The severe-turbulence QRH or SOP response, turbulence-penetration speed, altitude-change requests and diversion decisions are directed towards speed, attitude, altitude and continued safe operation. A failed flow in this group means that the described action did not become the stopping defence for the assessed sequence. Its relevant downstream risks are overspeed, aircraft upset, level bust and operational loss of margin, rather than occupant injury alone.

Minor injuries are the most prominent consequence remaining after a procedural action successfully stopped escalation, followed by No Consequence Events and smaller flows to operational consequences, overspeed, aircraft upset and level bust. This is not evidence that the procedure was ineffective. Cabin procedures are frequently applied shortly before, during or immediately after the encounter; they may limit the number or severity of injuries even when exposure has already begun. Similarly, a severe-turbulence procedure may contain an overspeed or upset after the initiating aircraft-state deviation has occurred.

The result makes procedures the clearest operational stopping layer in the ECR sample, but also shows why procedure performance should be assessed against a defined safety target. A seatbelt or cabin-securing

action cannot be judged by whether an overspeed occurred, and a penetration-speed action cannot be judged by whether an unrestrained passenger was injured. The strongest protection is therefore provided by coordinated use of cabin and aircraft procedures rather than by treating any single action as a complete turbulence defence.

Appendix D.3.1.4 **Situational awareness and action**

Situational awareness and action is classified as stopped in 22 %, and only 2.5% is classified as failed (Figure 119). The action-level picture is consequently more favourable than for the upstream barriers: once a relevant crew action is explicitly described, it is usually associated with containment rather than continued progression.

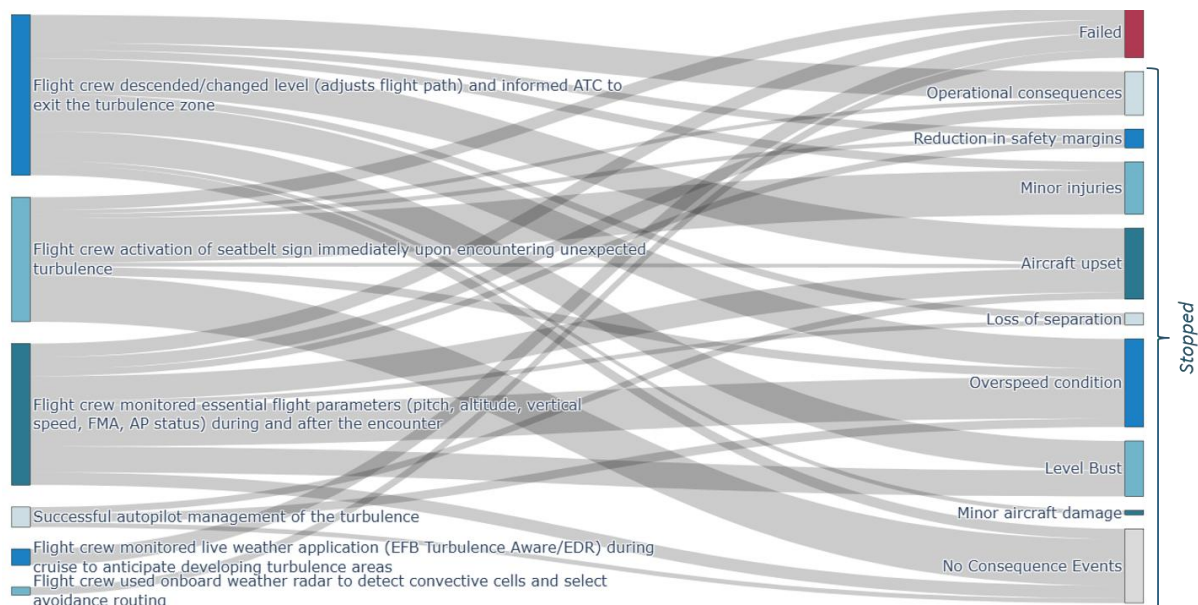


Figure 119 - Barrier type 4 actions, assessed effectiveness and linked consequential events

Aircraft-state recognition and control. Monitoring pitch, altitude, vertical speed, flight-mode annunciations and autopilot status, together with changing level or flight path and managing the autopilot, addresses the developing aircraft response. These actions are relevant to overspeed, upset, level bust, loss of separation and reductions in safety margins. Their function is adaptive: the encounter has already occurred, so success is measured by shortening the deviation, restoring a stable state or leaving the affected air mass.

Immediate occupant protection. Activation of the seatbelt sign after unexpected turbulence addresses the cabin pathway, but it cannot provide advance protection against the first acceleration. A stopped classification with a minor injury is therefore compatible with an action that reduced further exposure after the initial event. This timing difference helps explain why aircraft-state containment can be successful while a cabin consequence remains.

Continuing hazard awareness. Live weather applications and onboard weather radar can support tactical avoidance when usable information is available, but their contribution depends on turbulence type, update timing and the possibility of changing route or level. Their relatively small flows should not be compared directly with continuous parameter monitoring, which is relevant to virtually every encounter after it begins.

In this group, an operational consequence is often evidence of the barrier doing its job: a level change, route deviation or ATC-coordinated exit is the observable means by which exposure is reduced. Aircraft-state consequences similarly describe the condition being managed, not necessarily the failure of the corrective action. Situational awareness and action therefore form the main bridge between an encounter that could not be avoided and the later warning and recovery layers.

Appendix D.3.1.5 Warning systems operation and action

Warning systems are only assessed as stopped for 1.5% of the occurrences, while 0.8 % are classified as failed (Figure 120). This profile does not indicate weak warning-system performance. A warning becomes relevant only when the encounter generates a corresponding aircraft state or threshold exceedance.

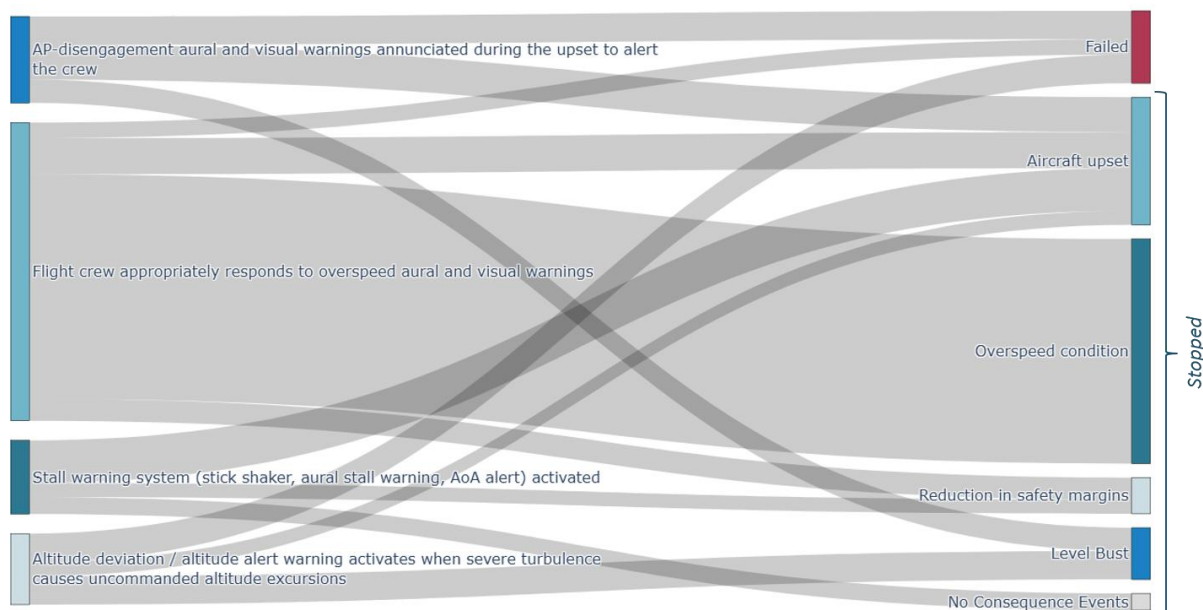


Figure 120 - Barrier type 5 actions, assessed effectiveness and linked consequential events

The figure shows distinct warning-response pathways rather than a generic turbulence alert. Overspeed warnings are linked mainly to overspeed conditions, stall or angle-of-attack warnings to aircraft upset and reduced safety margins, and altitude alerts to level busts. Autopilot-disengagement annunciation contributes the main failed flow. Because the warning was reported as having annunciated, this classification indicates that annunciation alone did not stop the assessed sequence; it does not demonstrate a technical failure of the warning system.

Among the stopped actions, overspeed is the most prominent linked event, followed by aircraft upset, level bust, reduction in safety margins and No Consequence Events. This apparent overlap is expected. The overspeed, upset or altitude deviation is often the condition that triggers the warning, so the warning cannot prevent the initial threshold exceedance. Its safety contribution is to prompt recognition and corrective action before that condition progresses towards structural damage, loss of control or a more serious separation event.

The absence of an injury-dominated pathway is equally informative. Aircraft warnings protect aircraft state and crew awareness; they do not provide advance cabin restraint or secure service equipment. A warning layer may therefore function correctly while a passenger or cabin-crew injury occurs. Therefore, while the warnings do not help avoid the condition, they are effective in ensuring it does not escalate to a high severity incident or an accident

Appendix D.3.1.6 Late recovery from a potential accident situation

Late recovery is classified as the stopping barrier in 1.3%, while failure is identified in only 0.02% (Figure 121). The distribution reflects the position of this group at the end of the event sequence: most occurrences were contained before a late-recovery action was required. While the cases shown in the action-level figure represent situations in which an injury, aircraft excursion or operational disruption had already occurred.

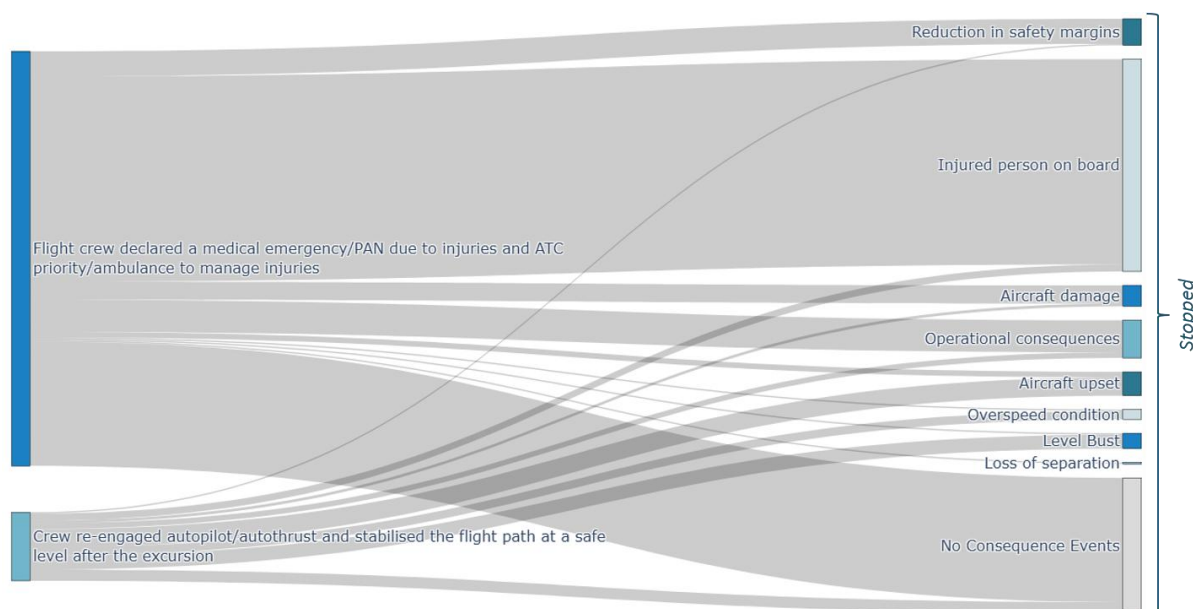


Figure 121 - Barrier type 6 actions, assessed effectiveness and linked consequential events

Late recovery performs two distinct functions once the occurrence has already developed. Medical emergency or PAN declarations, ATC priority and ambulance coordination mitigate an existing injury by accelerating access to care and supporting diversion. Similarly, re-engagement of autopilot or autothrust

and stabilisation of the flight path restore aircraft control after an excursion. The continued presence of injuries, operational consequences or aircraft-state deviations does not indicate that recovery failed, as these actions aim to prevent further escalation rather than remove consequences that have already occurred.

The prominence of injuries in the medical-recovery pathway and No Consequence Events in part of the aircraft-stabilisation pathway reflects these two functions: limiting the severity of an existing consequence and preserving residual aircraft control. The large Remaining share should not be interpreted as an effectiveness rate; it mainly indicates that late recovery was not required because most occurrences were contained by earlier barriers, leaving this group available as a final resilience layer.