



Co-funded by
the European Union



ALBATROS Project

Directed study on in-flight turbulence

Dissemination Event

29th September 2026

In collaboration with:



EASA

ALG

Welcome to this webinar



This webinar is the dissemination event of a safety study carried out within the ALBATROS research project

FUNDING



Horizon Europe

The ALBATROS project is funded by the European Union's Horizon Europe research and innovation programme

CONSORTIUM



NLR, EASA and D4S

EASA and the Data4Safety (D4S) programme are members of the ALBATROS Consortium, led by NLR

TODAY'S SCOPE



In-flight turbulence

One of the project's research topics was a directed study on in-flight turbulence, the subject of today's session

Today's speakers:



Léopold Viroles
D4S Programme Manager



Rombout Weaver
NLR Senior
Safety Consultant



Pablo González
ALG Consultant



Núria Alsina
ALG AI & Digital
Transformation Principal



Carles Molins
ALG Team Leader

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TODAY'S SCOPE



In-flight turbulence

One of the project's research topics was a directed study on in-flight turbulence, the subject of today's session

...but many others participated:



Florent Morel
D4S Operations Manager



Wouter van Engelen
ALBATROS Project Coordinator



Jeroen van Rooij
Captain 777/787 and safety expert



**Safety Issue Assessment (SIA)
Turbulence Task Team**
EASA experts



Gerard van Es
Principal consultant flight
operations and safety

Agenda for today's session

1 Introduction and background

2 Data sources and methodology

3 Main findings

- Characterisation of turbulence encounters
- Analysis of consequential events
- Safety barrier performance

4 Conclusions and way forward

5 Q&A

6 Closing remarks

Questions & comments



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Advanced systems and solutions for better practices against hazards in the aviation system



2022–2026

Project duration



€8M+

Total funding
Horizon Europe



33

Deliverables
across the project



21

Consortium
partners

More about the project: www.albatros-horizon.eu

Why ALBATROS?

Improve resilience to emerging and future hazards and increase survivability



Emerging & future hazards

Extreme weather • space weather • climate change impacts • cybersecurity



New fuels & energy systems

Hydrogen-fuelled and hybrid-electric aircraft introduce new operational and safety risks.



New aircraft entrants

Drones and Urban Air Mobility vehicles require new approaches to safety risk assessment.

Why in-flight turbulence?



Climate change is expected to increase the **likelihood** and **intensity** of **in-flight turbulence**, highlighting the need for a **data-driven** understanding of this **emerging safety hazard**



THIS DIRECTED STUDY



**In-flight turbulence,
through EASA Data4Safety**



Study turbulence **analytically**



Look **beyond** the encounter itself



Work at **European scale**



Demonstrate **D4S capabilities**



Open up **future research**

Data4Safety brings together European-scale aviation data, safety expertise and advanced analytical capabilities to strengthen the study and enable cross-industry collaboration



Supported by



Programme members

28	14	9	8	3	2
National Aviation Authorities	Air Operators	ATM / ANSP	Airports	Aircraft Manufacturers	Professional Representative Bodies

Platform & Analytics Provider



Audience interaction



What topics related to in-flight turbulence are you most interested in today?

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Data sources and methodology

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Data sources

*European Central Repository

	Geographical scope
	Time scope
	Data volume
	Data provider

ECR* safety occurrence reports 
Worldwide <i>subject to Regulation (EU) 376/2014</i>
2015 - 2025
4 M Safety occurrence reports
European Central Repository

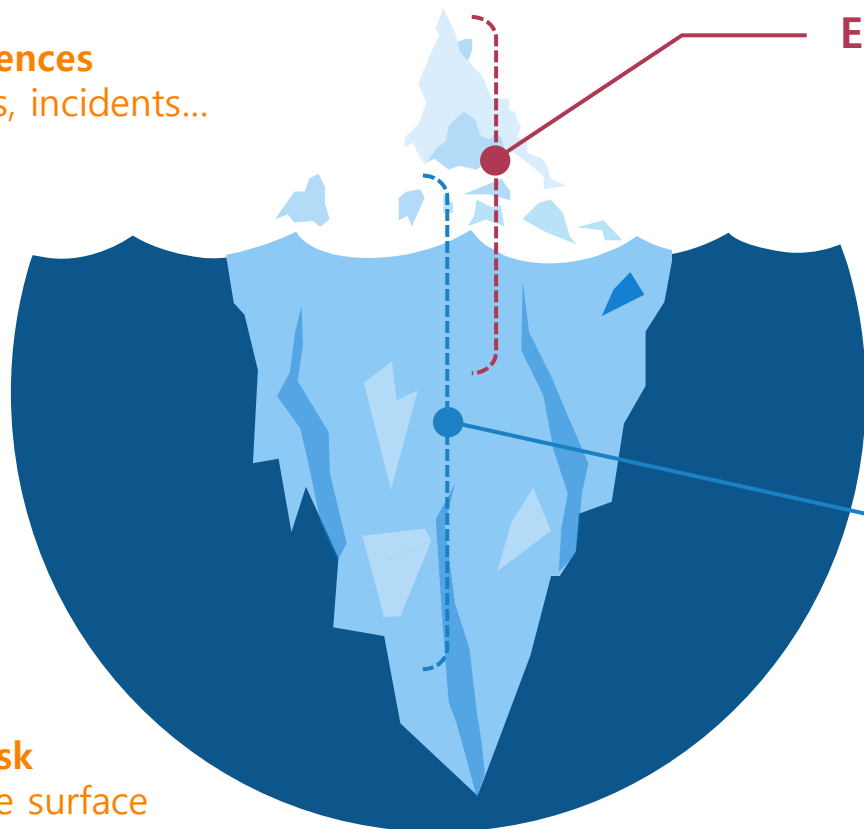
Recorded flight data 
Europe
2023 - 2025
4.4 M Flights
6 European Operators

The complimentary nature of ECR and recorded flight data

Visible consequences

Accidents, incidents...

ECR data



Latent risk below the surface

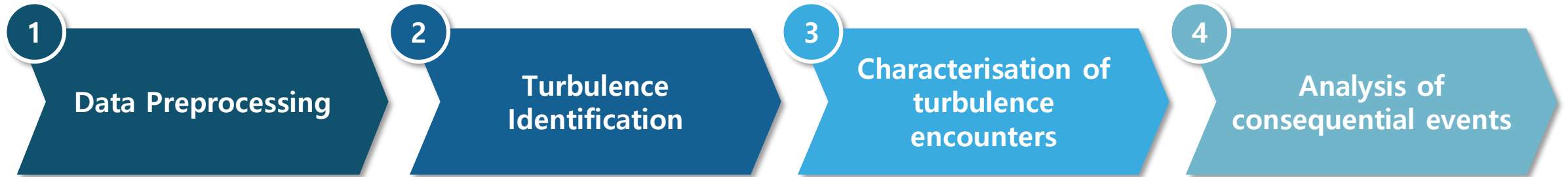
- **Reported turbulence:** events that may represent a significant risk to aviation safety¹, including severe turbulent events²
- Measures the **subjective, reported intensity** of the turbulent encounter
- Biased towards events with **actual or potential consequences**

Recorded flight data

- **Identifies actual exposure to turbulence**, irrespective of consequences or outcomes
- Measures the objective, threshold-based **magnitude of the aircraft response** to turbulent gusts
- In the context of climate change and possible increase of turbulence encounters, allows **monitoring of latent risk**

¹ According to Reg (EU) 376/2014
² According to Reg (EU) 923/2012

Analytical framework



Data preprocessing



Geographical 

Temporal 

Aircraft Type 

Flight Phase 

Turbulence Type 

Directed
Study
Scope

Worldwide

ECR
2015-2025
Flight data
2023-2025

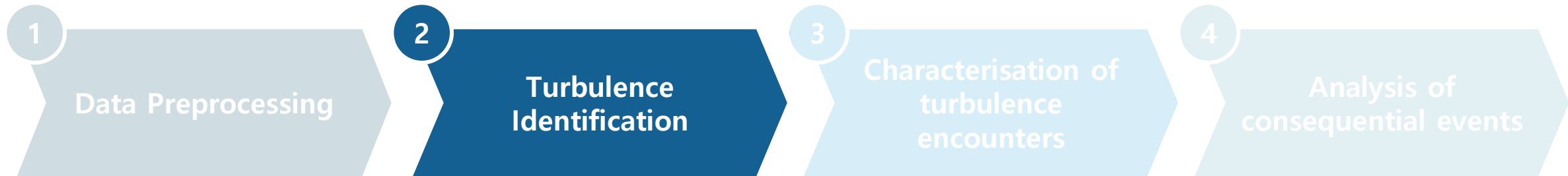
**Large Commercial
Transport Aircraft***

**Initial Climb
Climb
Cruise
Descent
Approach**

**Clear Air
Turbulence
&
Convective
Turbulence**

* Refers to *CAT Complex Aircraft*, as defined by EASA in Regulation (EU) No 965/2012

Ad-hoc turbulence identification methodology



ECR safety occurrence reports



- **Keyword-based** search combined with **LLM enhancement** of low reported attributes
- Retrieval of **turbulence-specific attributes** from the occurrence narratives

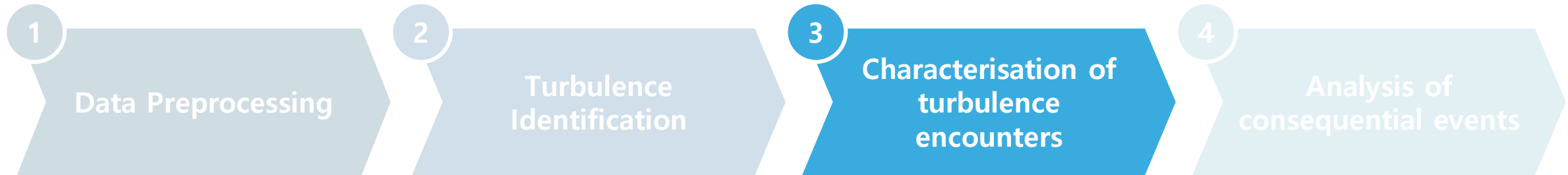
Recorded flight data



- Turbulence identification methodology based on the RMS* of the **vertical accelerometer** signal
- **High-pass filter** to separate turbulences from manoeuvres

* RMS = Root Mean Square

Turbulence characterisation



Turbulence characterisation

Analysis across different dimensions on both data sources

Turbulence type



Intensity level



Flight level

FL

Altitude



Geographical



Route type



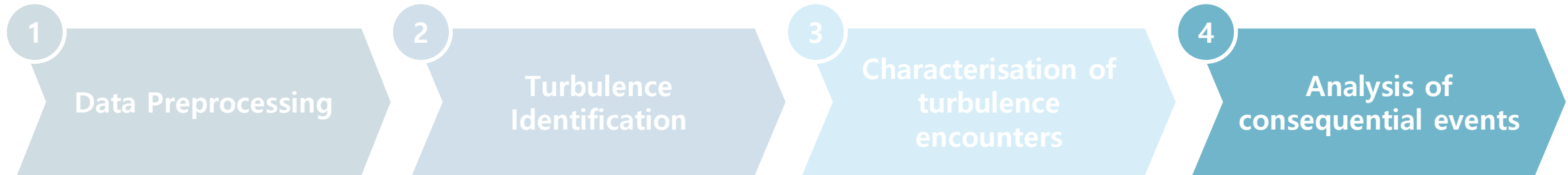
Flight phase



Seasonality



Consequential events



Consequential events

Looking beyond the turbulence event itself

Injuries

Aircraft damage

Loss of separation

Level bust

AP disengagement

High load events

Overspeed

Aircraft upset

TCAS RA



Main findings

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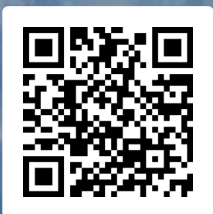
Topic #1

What is the frequency of turbulence encounters?

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Physical exposure to turbulence

>827,000
turbulence episodes

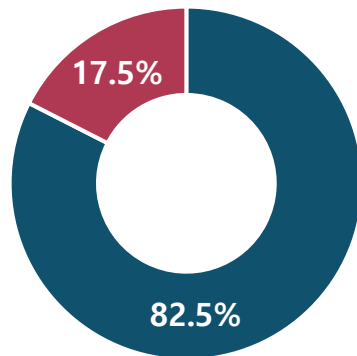
197
episodes per 1,000 flights

53.6 s
average episode duration

0.48 g
average vertical load deviation

Flights affected by turbulence

Recorded flight data

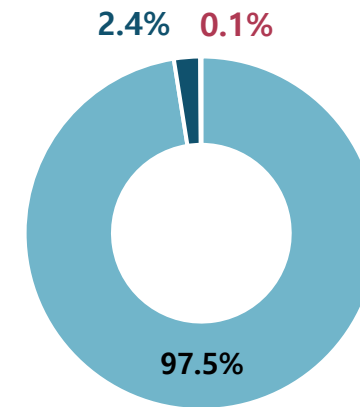


17.5%
of flights contain at least one
turbulence episode

82.5%
of flights are free of turbulence

Breakdown by intensity level

Recorded flight data



0.1%
severe turbulence episodes
($\text{RMS}^* > 0.3$)

2.4%
moderate turbulence episodes
($0.2 < \text{RMS}^* < 0.3$)

97.5%
light turbulence episodes
($0.1 < \text{RMS}^* < 0.2$)

* RMS = Root Mean Square

Frequency of reported turbulence

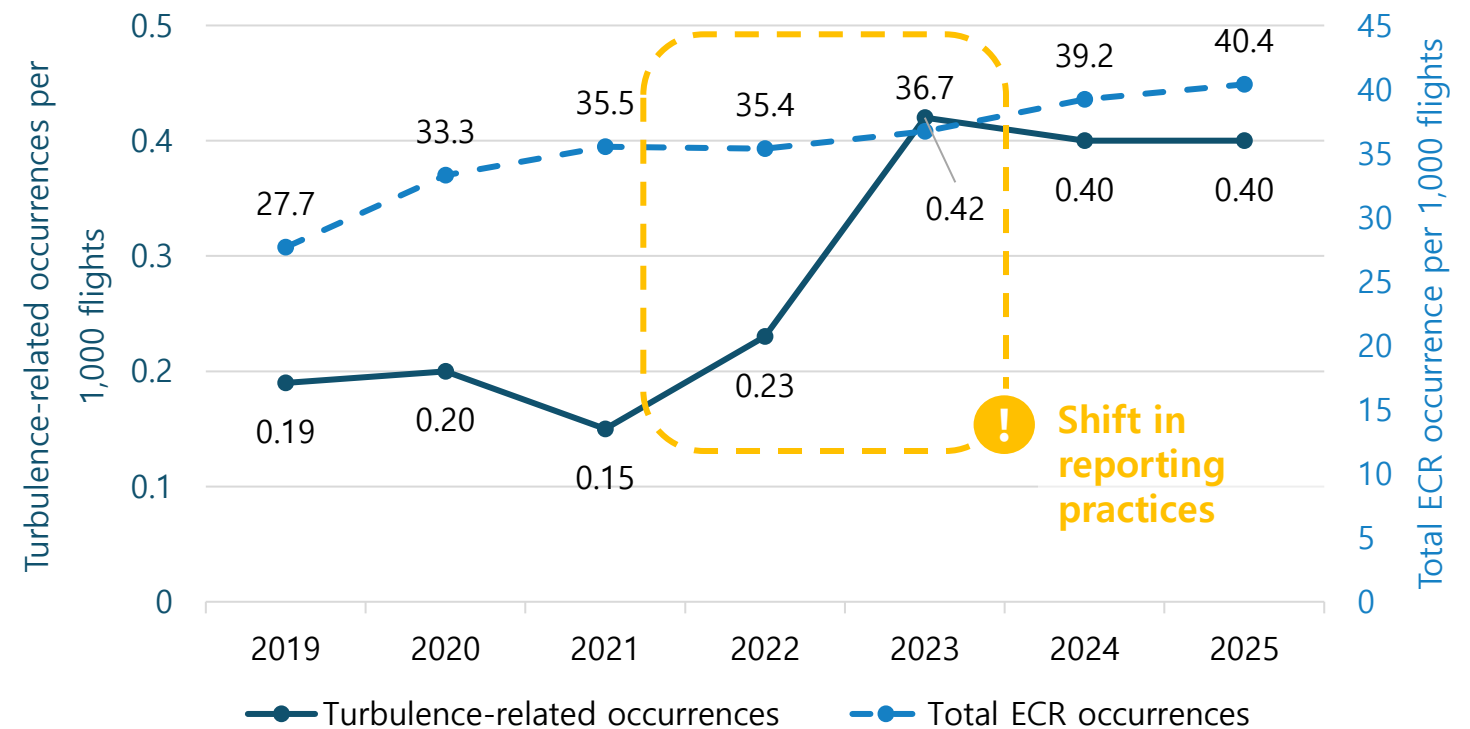
22,004

reported turbulence-related occurrences

Turbulence-related occurrences:
1 in 3,600 flights

Annual rate of reported turbulence and total ECR occurrences per 1,000 flights

ECR data





Topic #2

How do turbulence encounters vary by flight phase?

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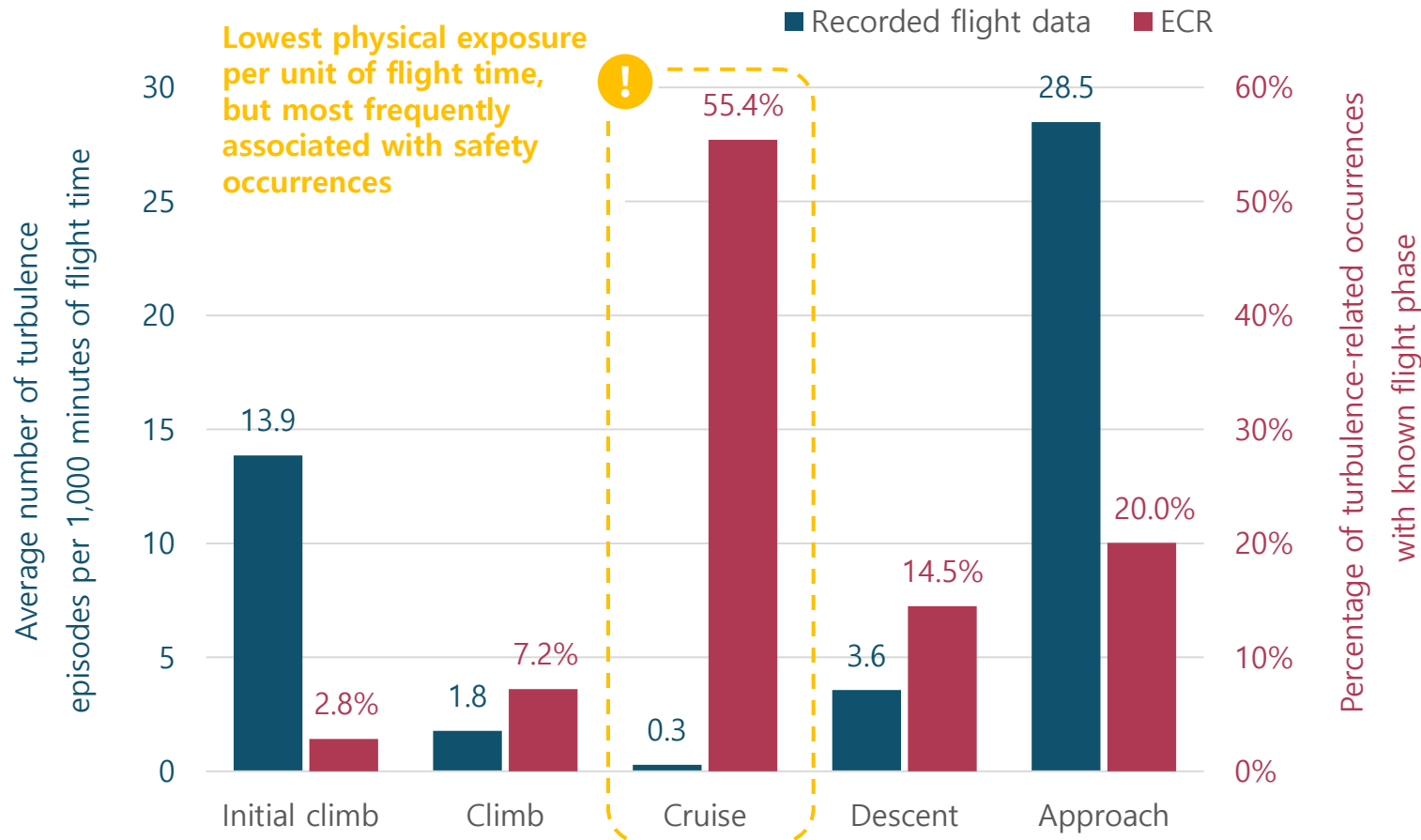


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Flight phase shapes exposure and reporting

Distribution of flight phase in turbulence encounters

Recorded flight data & ECR data



Measured turbulence is concentrated at low altitudes and at end of flight

- 1 **Weather** and **topology-related** phenomena
- 2 Changes in **aircraft response** (density, wing loading)
- 3 Less **operational flexibility** than in cruise

In ECR, cruise is largely dominant

- 1 **Cabin activity**
- 2 **Less predictability** of CAT
- 3 Higher likelihood of **consequences** such as injuries



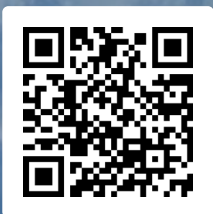
Topic #3

What types of turbulence do we observe in the encounters?

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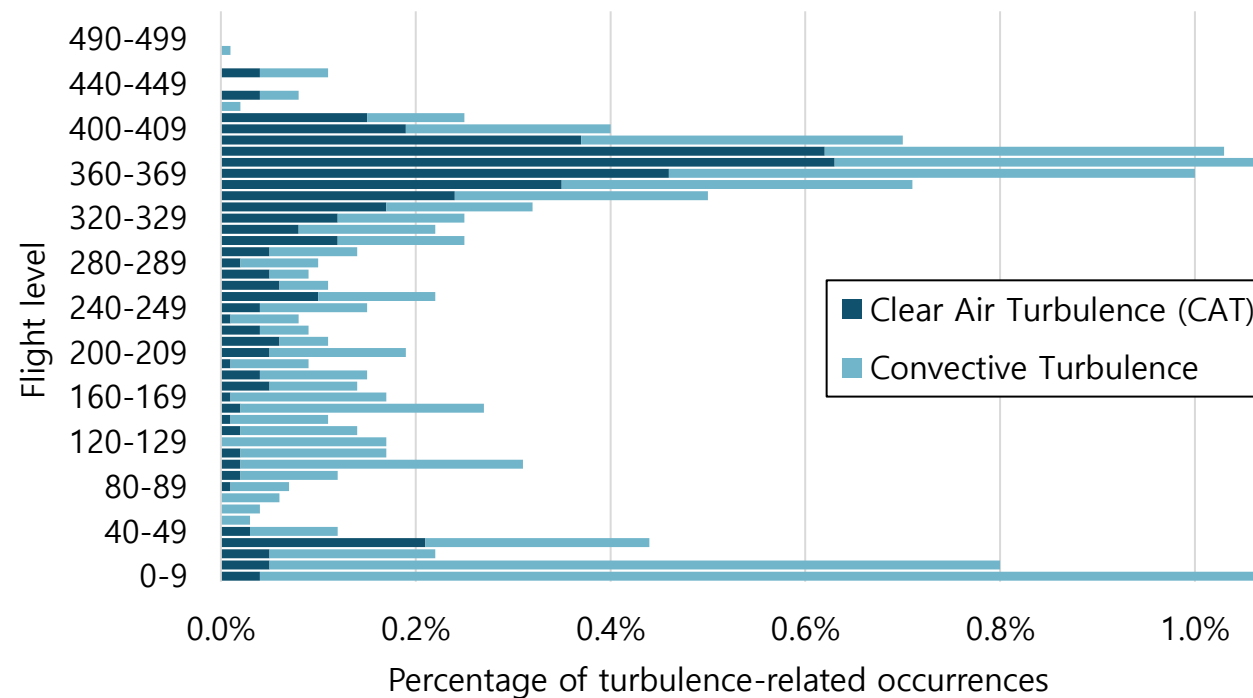


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The role of turbulence type

Distribution of turbulence type by flight level

ECR data



Lower predictability
(weather radar)

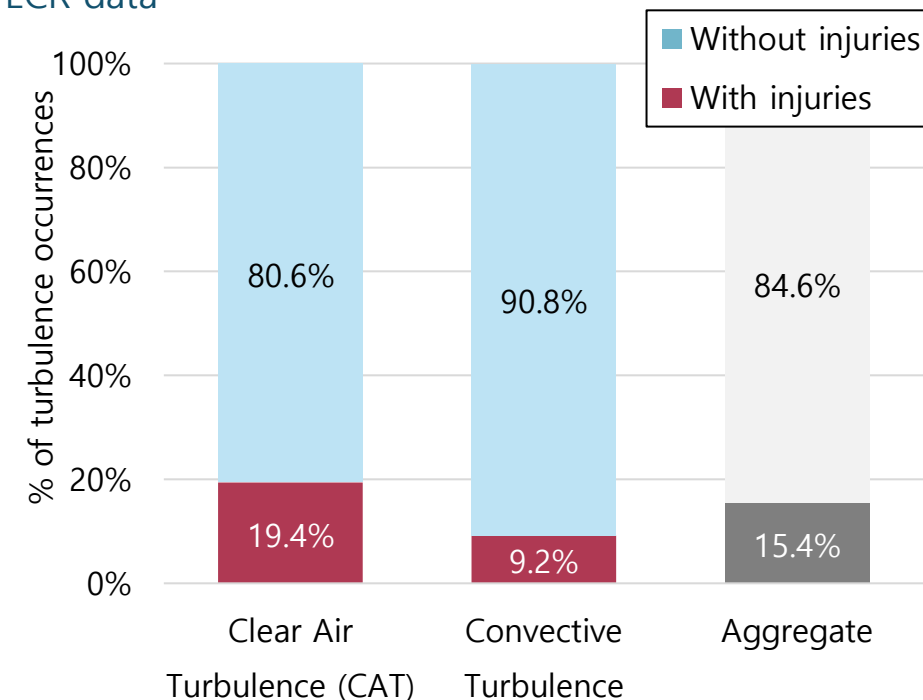
+

Predominance in
cruising altitudes

=

Likelihood of injuries by turbulence type

ECR data



Higher injury likelihood for CAT
encounters



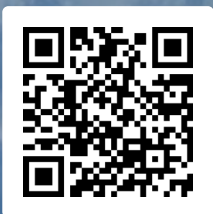
Topic #4

The role of on-board weather radar

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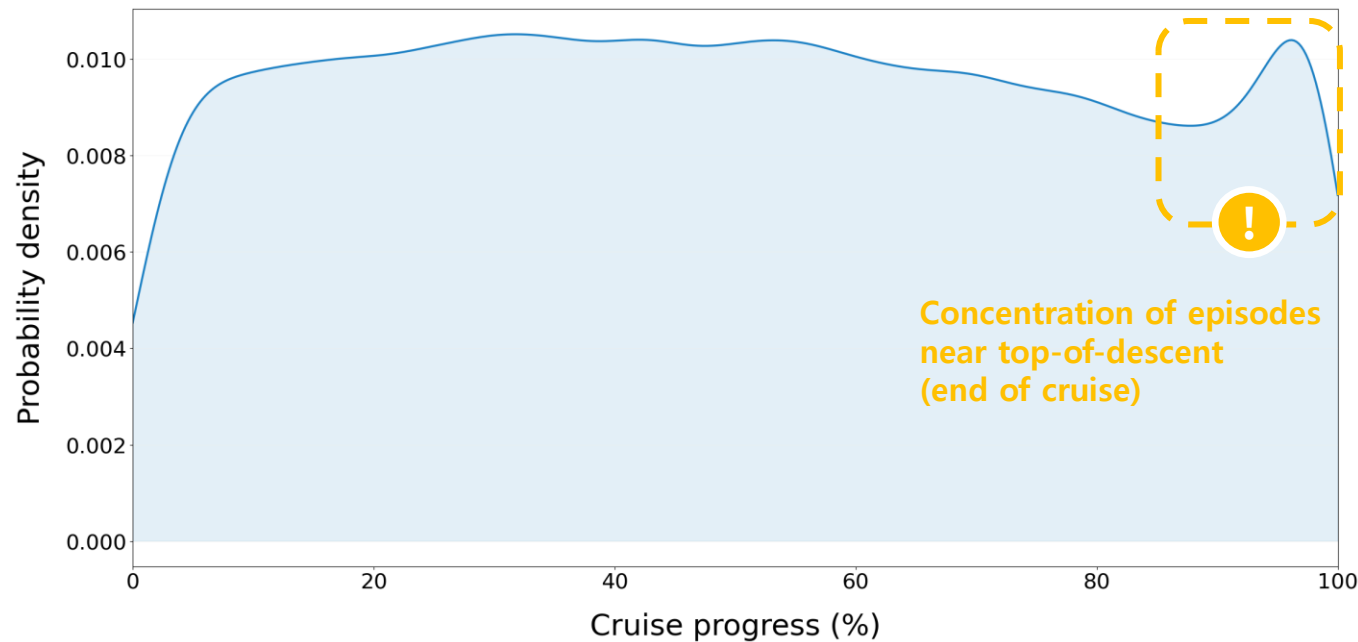


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The late-cruise turbulence peak: a hypothesis

Distribution of turbulence episodes during cruise

Recorded flight data

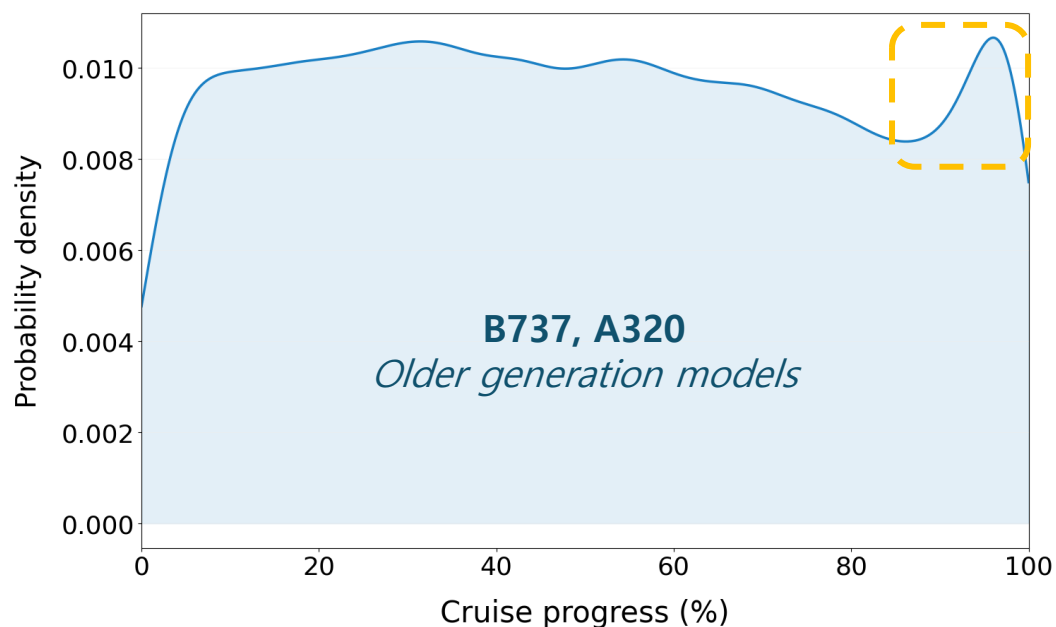
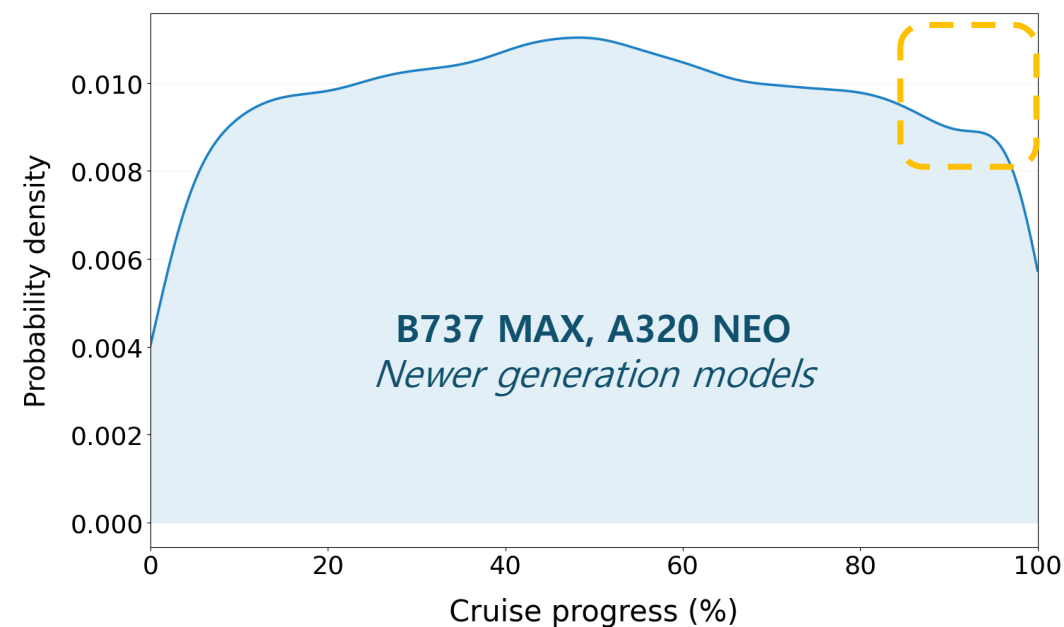


- 1 Management of on-board weather radar and **detection limitations due to manual tilt and gain settings** near top of descent
- 2 Crew proficiency in **radar adjustment** and/or insufficient attention given to radar adjustment in SOPs
- 3 **High workload** in transition from cruise to descent

Testing the hypothesis: the role of radar technology

Distribution of turbulence episodes during cruise by aircraft generation

Recorded flight data





Topic #5

What consequences do turbulence encounters create?

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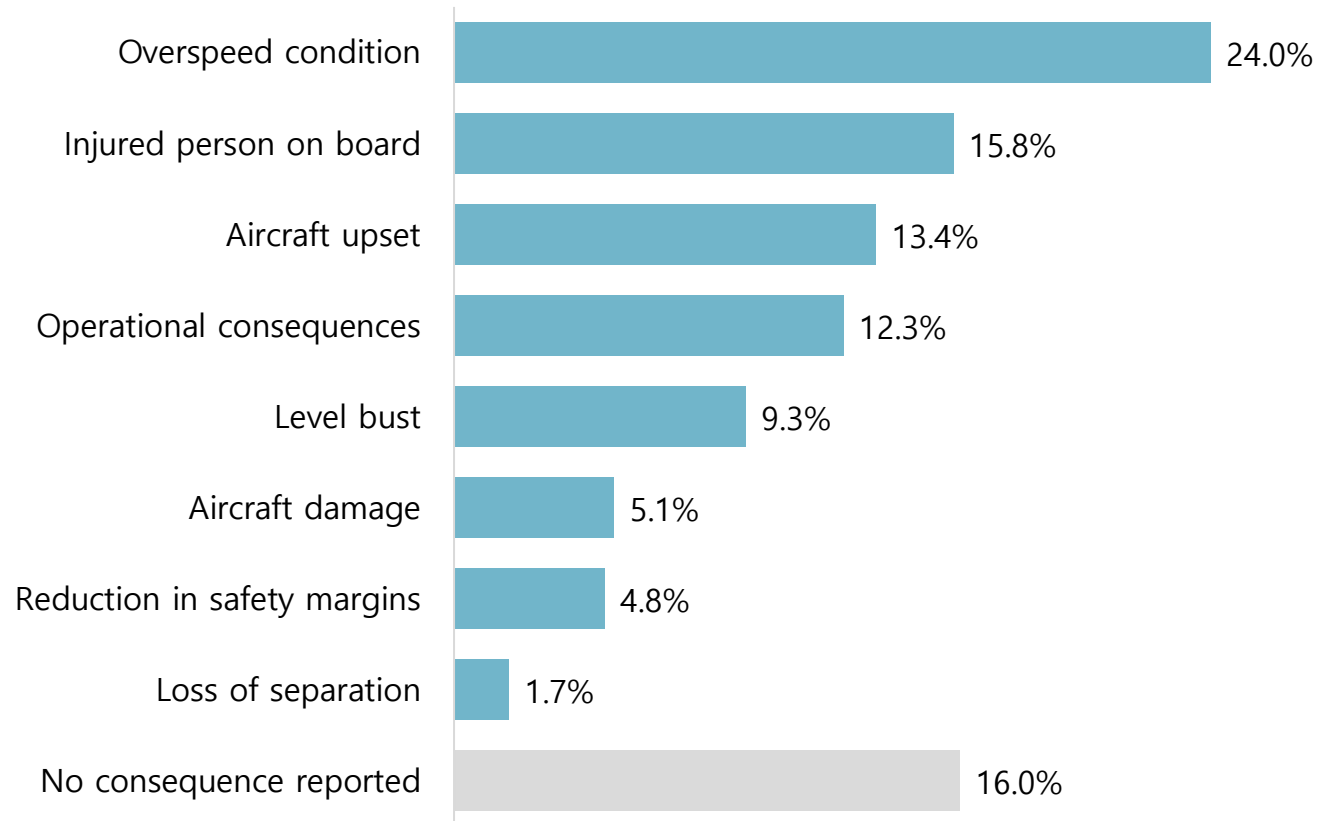
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Consequences drive ECR reporting

Distribution of consequential events in turbulence occurrences ECR data

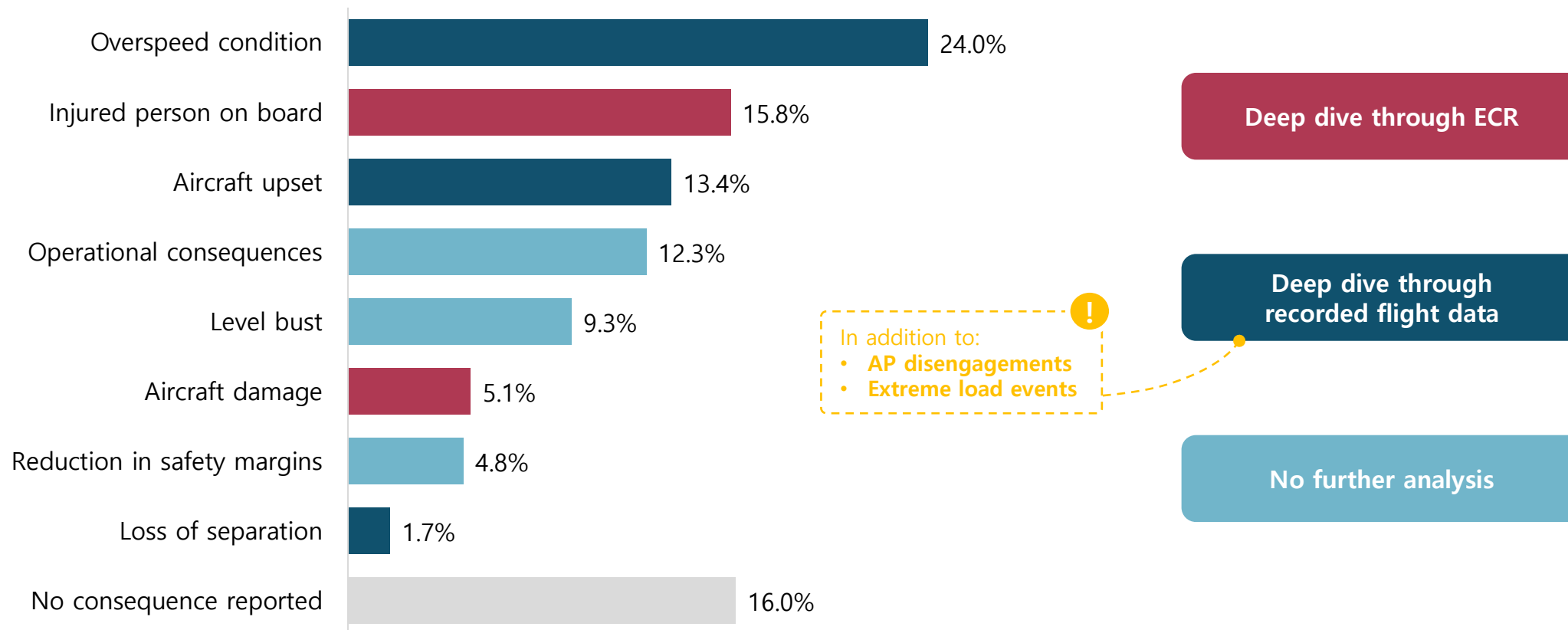


84%
with a reported consequence

Shows the ECR bias towards events with consequences,
in accordance with Regulation (EU) 376/2014

Consequences drive ECR reporting

Distribution of consequential events in turbulence occurrences ECR data





Topic #6

What are the characteristics of turbulence-related injuries and aircraft damage?

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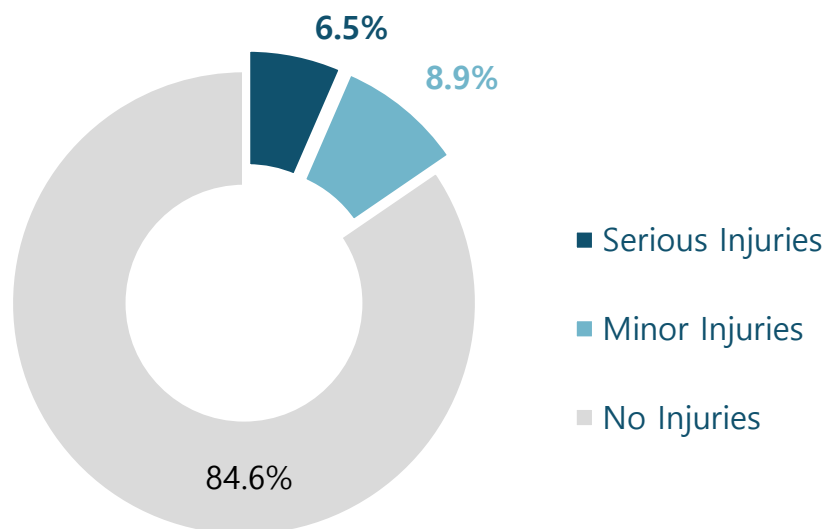
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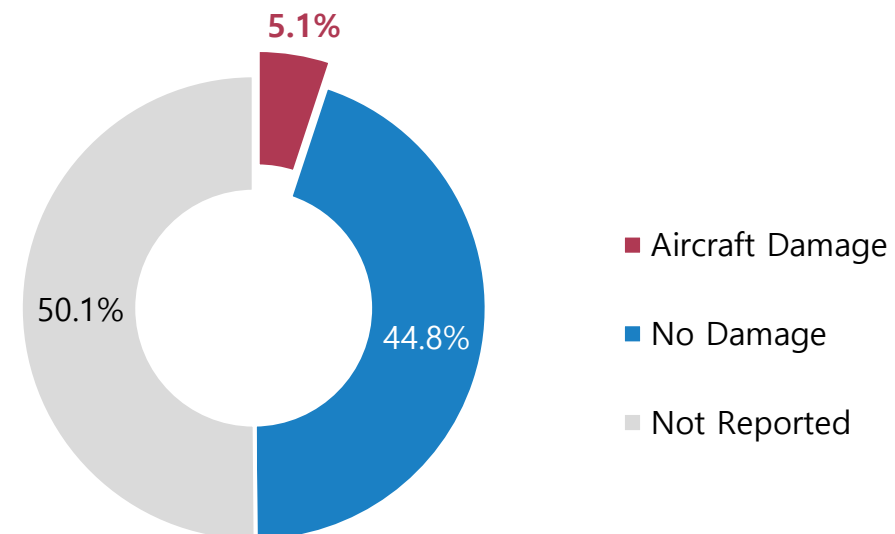
Injuries are much more common than aircraft damage

Injuries in turbulence occurrences
ECR data



15%
with reported injuries

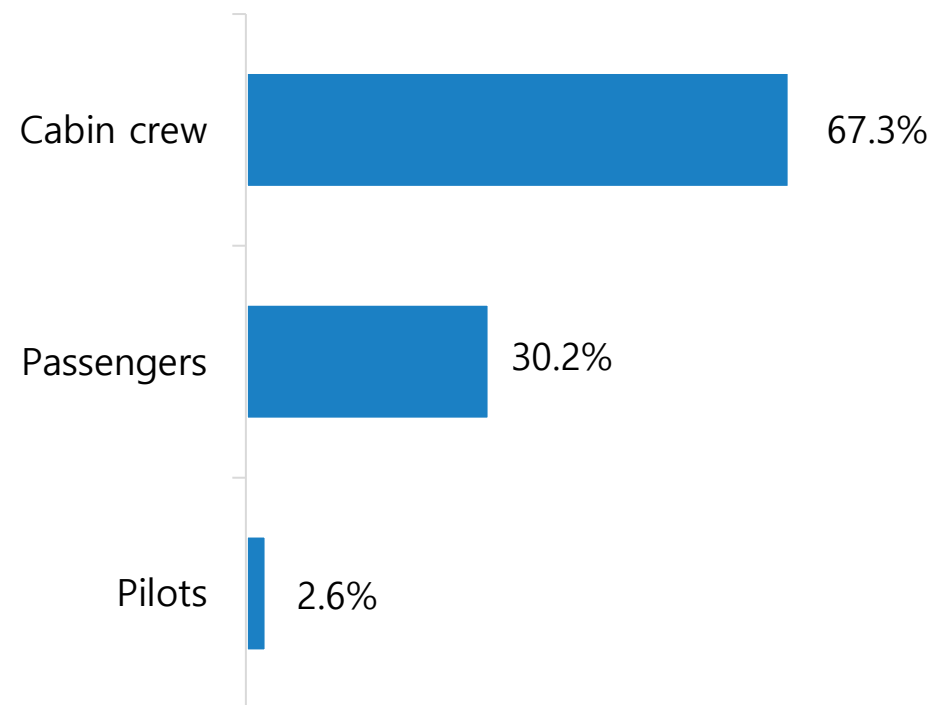
Aircraft damage in turbulence occurrences
ECR data



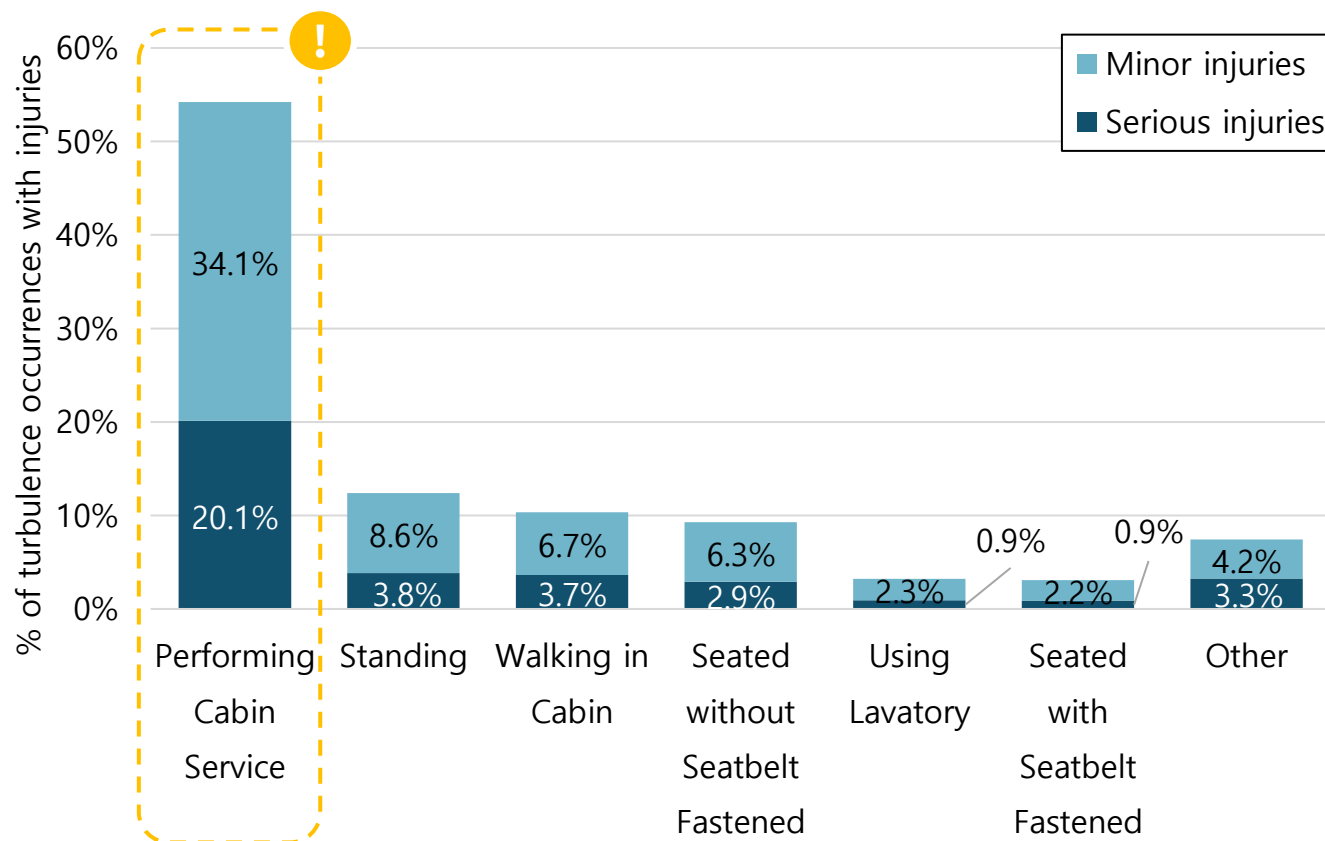
5%
with reported damage

Cabin crew activity links cruise to injuries

Distribution of injuries by affected personnel
ECR data

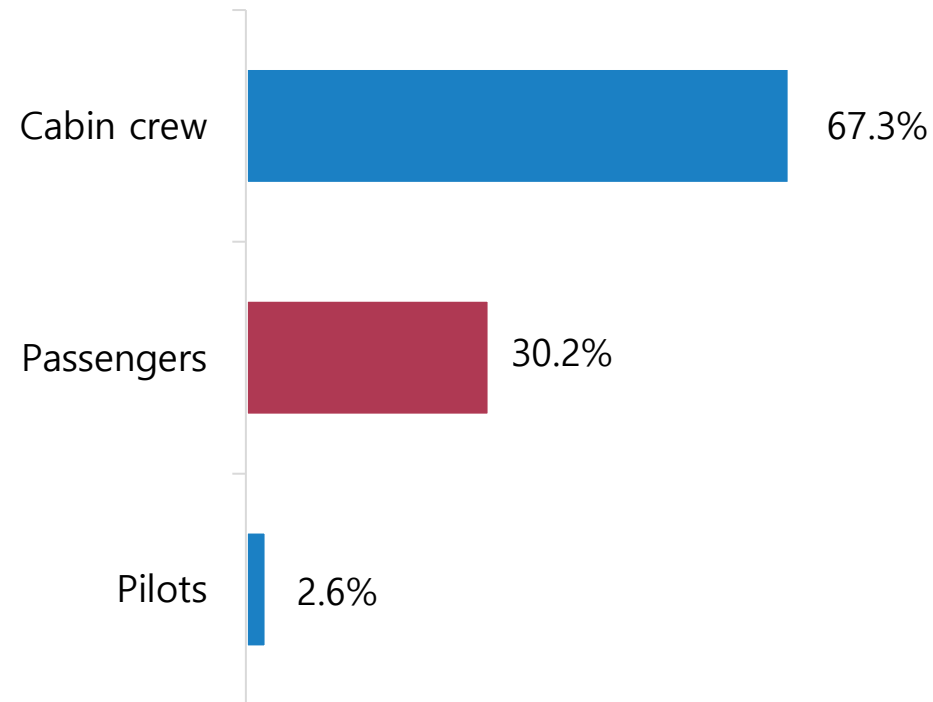


Cabin crew: Activity during injury
ECR data

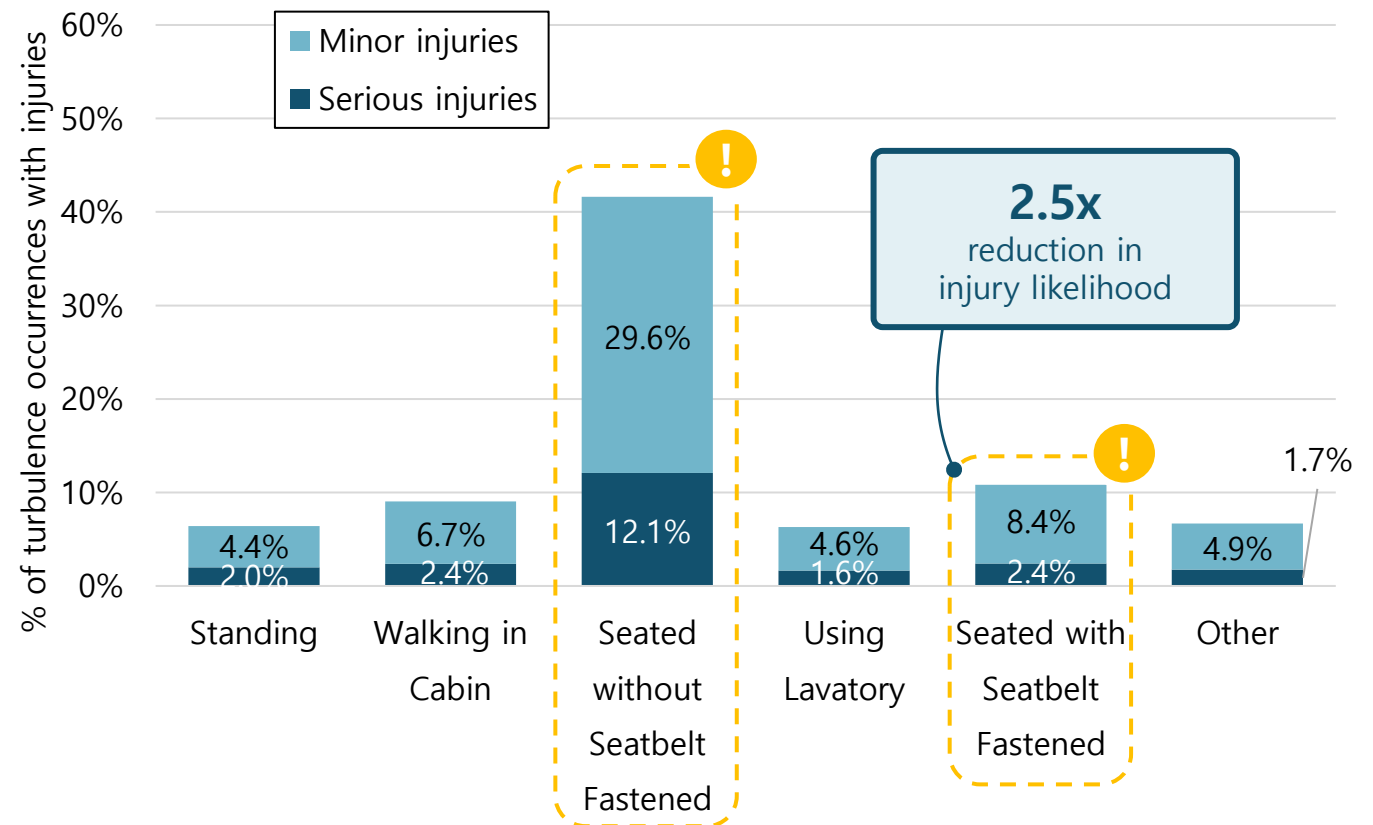


Lack of restraint drives passenger injury risk

Distribution of injuries by affected personnel
ECR data



Passengers: Activity during injury
ECR data





Topic #7

What are the key consequences of turbulence identified in the recorded flight data?

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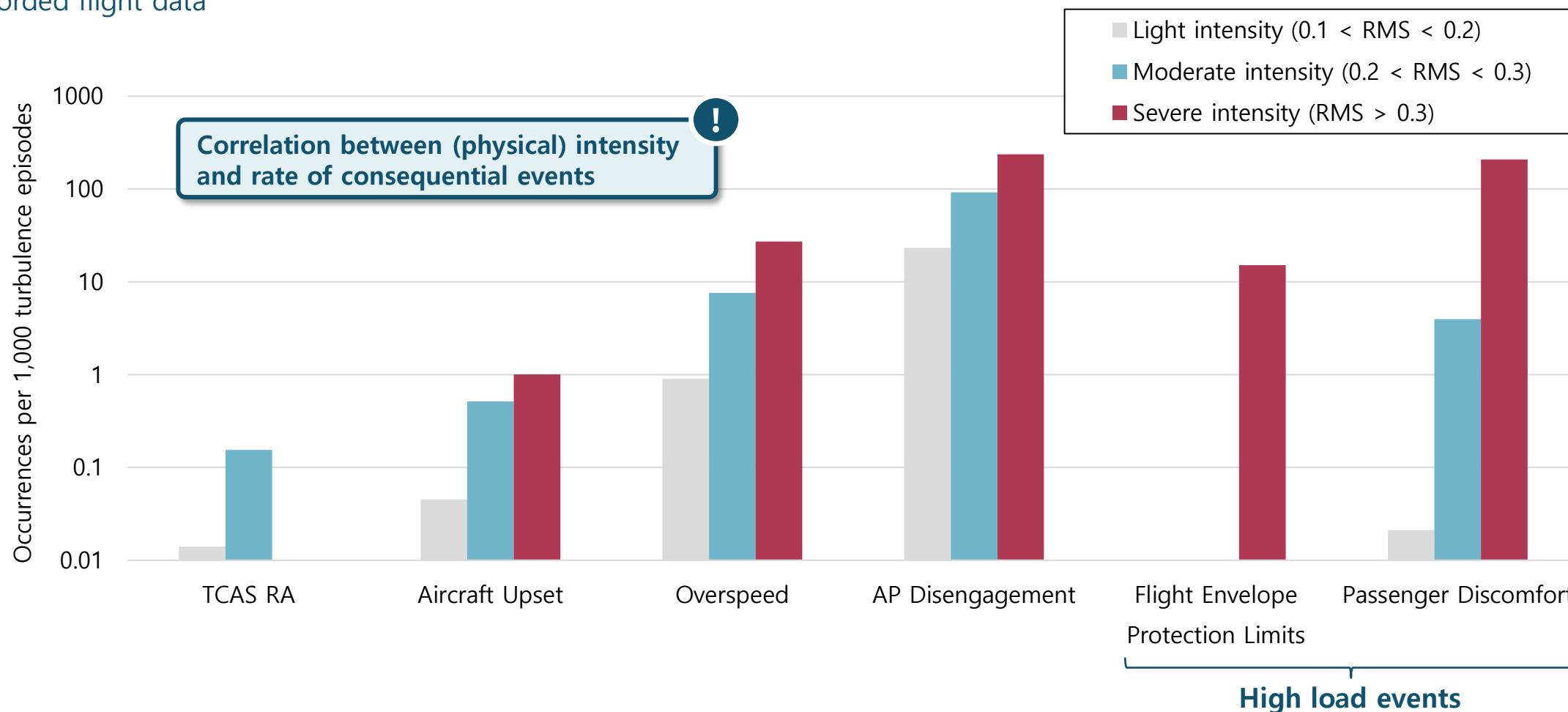


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Consequences increase with aircraft response intensity

Exposure to consequential events

Recorded flight data

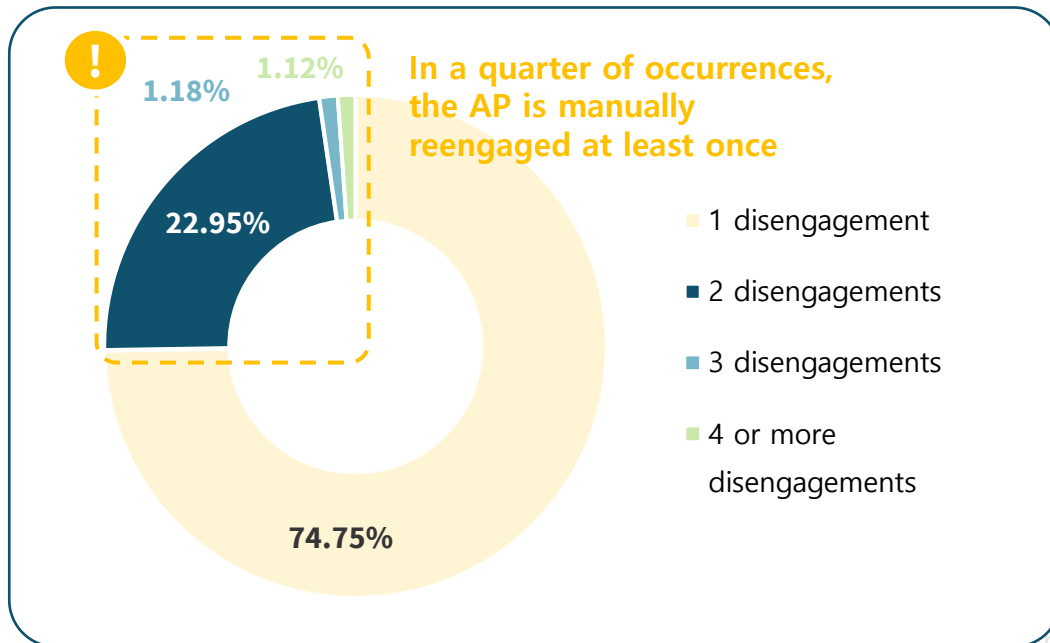
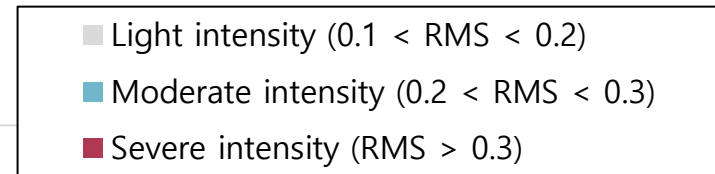
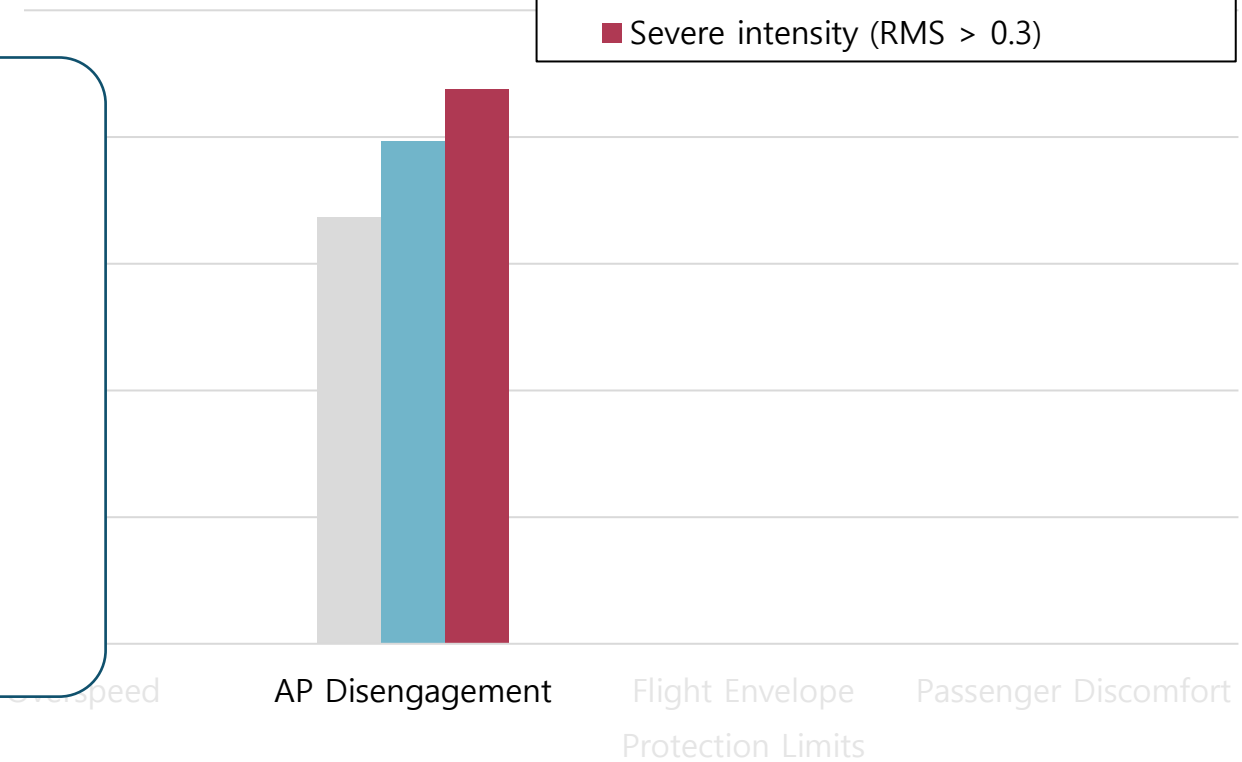


Autopilot disengagement

Exposure to consequential events

Recorded flight data

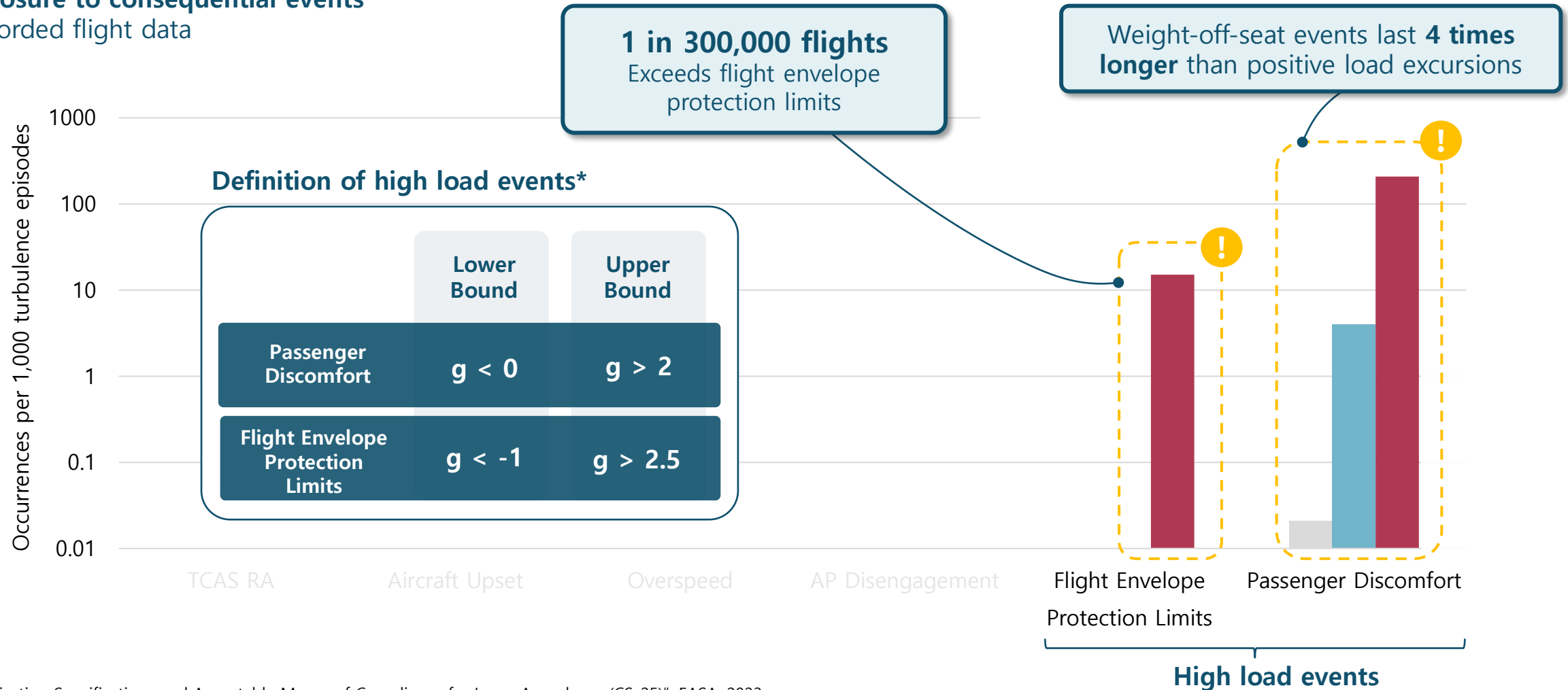
Breakdown by number of disengagements



Extreme load events

Exposure to consequential events

Recorded flight data

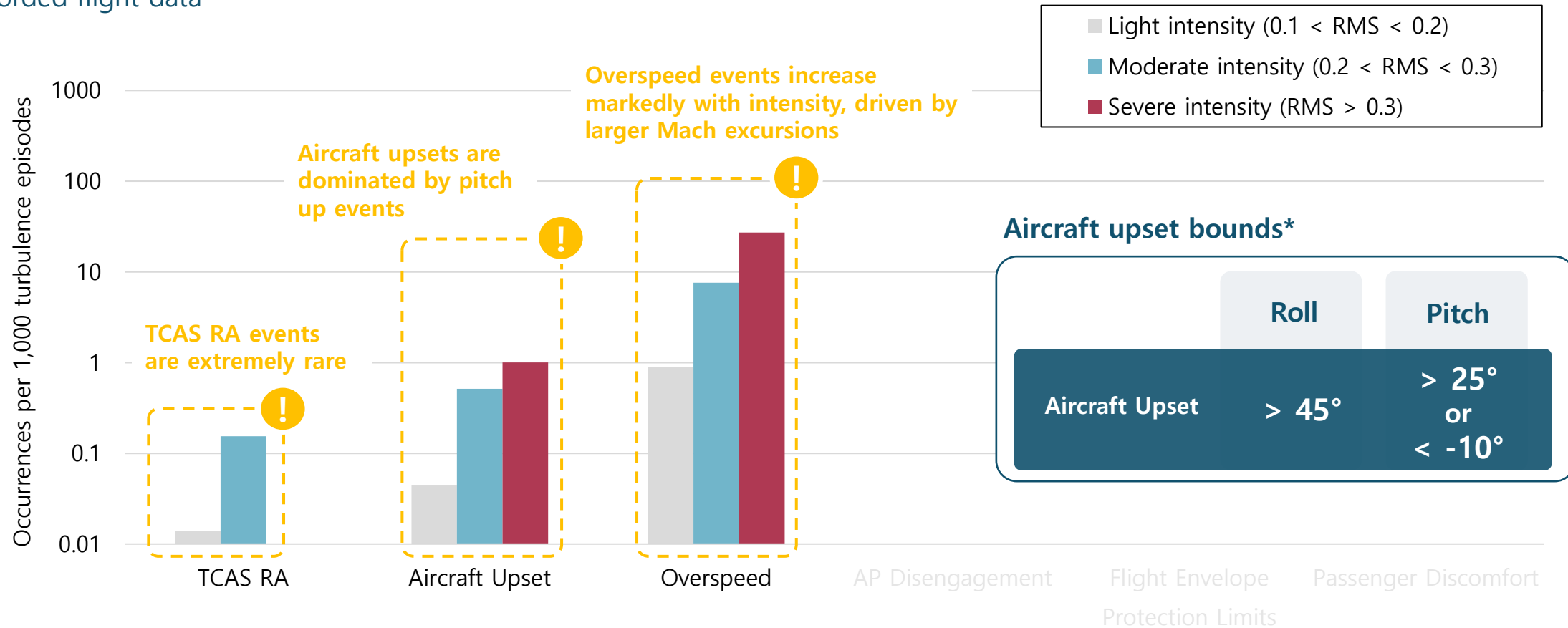


* See "Certification Specifications and Acceptable Means of Compliance for Large Aeroplanes (CS-25)", EASA, 2023

Aircraft upsets, overspeed events, and TCAS RA

Exposure to consequential events

Recorded flight data



* Based on EASA and FAA definitions



Topic #8

How effectively do safety barriers prevent or mitigate turbulence encounters?

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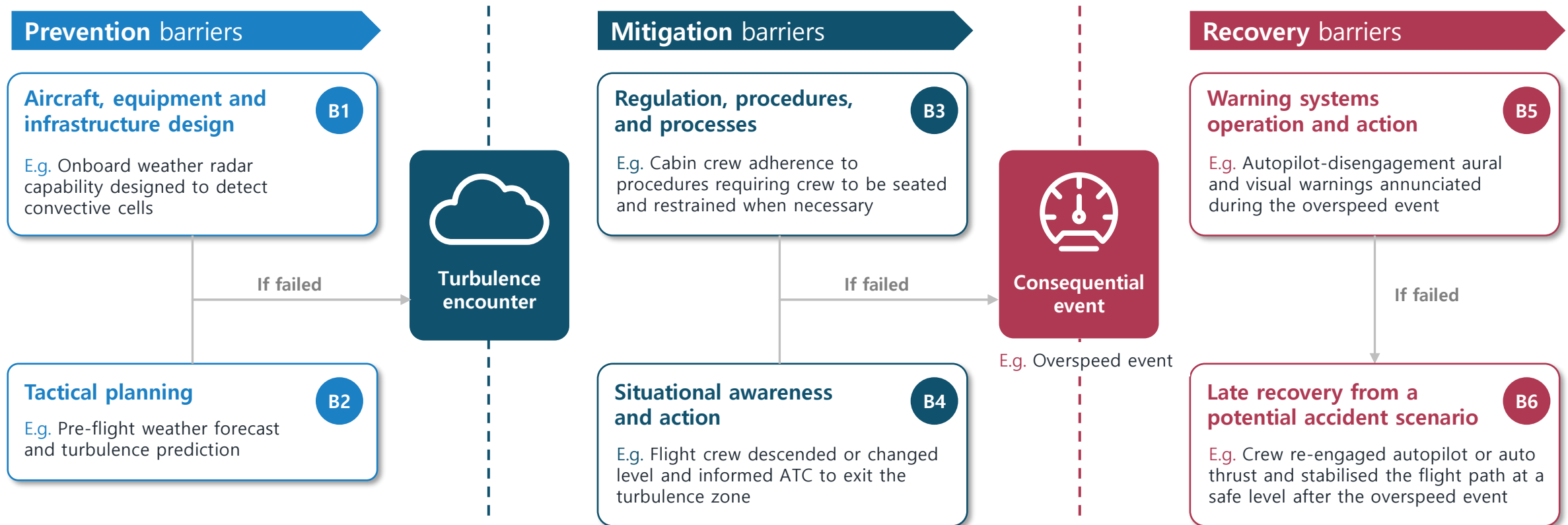


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ERCS defines the barriers, LLMs assess their effectiveness

The European Risk Classification Scheme (ERCS)* framework in action

Example: Turbulence-induced overspeed event

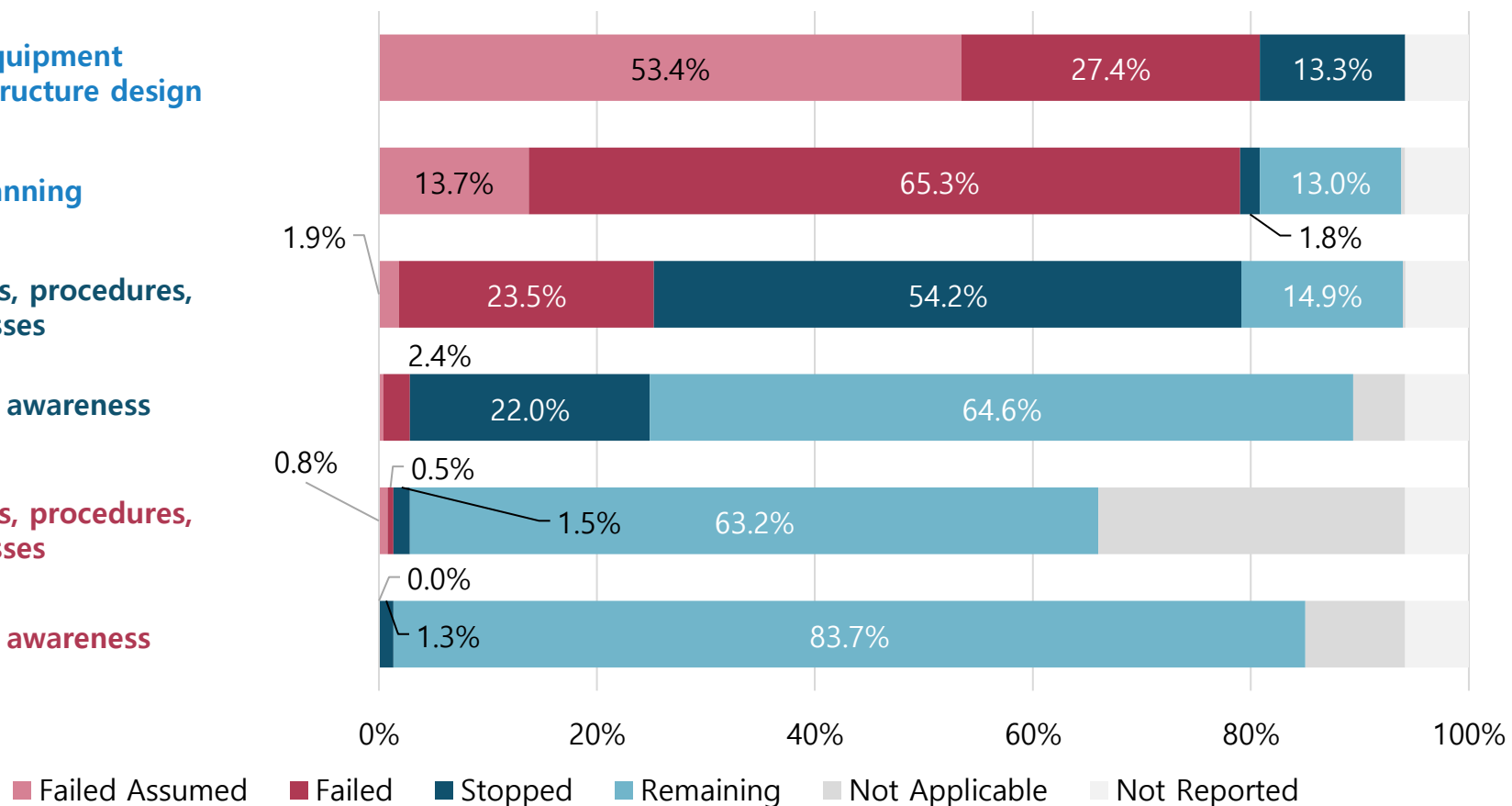


* The ERCS was formally established by the European Commission through Delegated Regulation (EU) 2020/2034, becoming fully operational in January 2023

Crew awareness and SOPs contain turbulence consequences



- PREVENT**
- B1** Aircraft, equipment and infrastructure design
 - B2** Tactical planning
- MITIGATE**
- B3** Regulations, procedures, and processes
 - B4** Situational awareness and action
- RECOVER**
- B5** Regulations, procedures, and processes
 - B6** Situational awareness and action



Audience interaction



Discussion of **audience feedback**

*What topics related to in-flight turbulence
are you most interested in today?*

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Conclusions and way forward

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Conclusions related to in-flight turbulence

Turbulence characterisation

- 1 Two risk profiles**
Severe turbulence is rare but with high-consequence; light turbulence is frequent and with lower consequence
- 2 Occupant vulnerability matters**
Injuries are linked to unrestrained occupants and ongoing cabin service
- 3 Early warning is key**
Timely information enables cabin preparation and cabin service suspension
- 4 CAT poses greater risks**
CAT is harder to detect and often occurs during cruise, causing more injuries

Consequential events and barriers

- 1 Consequences increase with intensity**
Overspeed and autopilot disengagement are the most frequent consequences; more severe consequences remain rare
- 2 Lack of restraint drives passenger injury risk**
There is a 2.5x reduction in injury likelihood when the passenger seatbelt is fastened
- 3 Repeated AP disengagements are noteworthy**
In around one quarter of events, the AP is manually re-engaged before being disengaging again
- 4 Safety relies on layered barriers**
Technical, operational and human barriers jointly prevent escalation

The effects of a warming climate



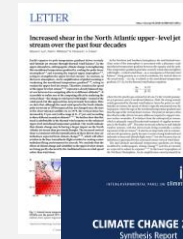
Climate change is increasing turbulence*

- Strong and growing scientific consensus that **anthropogenic warming** is increasing in-flight turbulence
- **Clear-air turbulence** (CAT) shows the **most consistent correlation** with climate change (2-3× increase by 2050-2080¹)
- **Convective turbulence** is also **likely to intensify** (more frequent severe thunderstorms across Europe by 2100²)



European Plan for Aviation Safety (EPAS)

EASA Scientific Committee Annual Report



Peer-reviewed research



Climate benchmark

Key takeaways



Improved detection and forecasting of CAT should be a priority to mitigate the risk associated with injuries caused by its low predictability and the high level of cabin activity during cruise



Continued **advancements of onboard weather radar technology** will play a key role in adequately managing convective turbulence

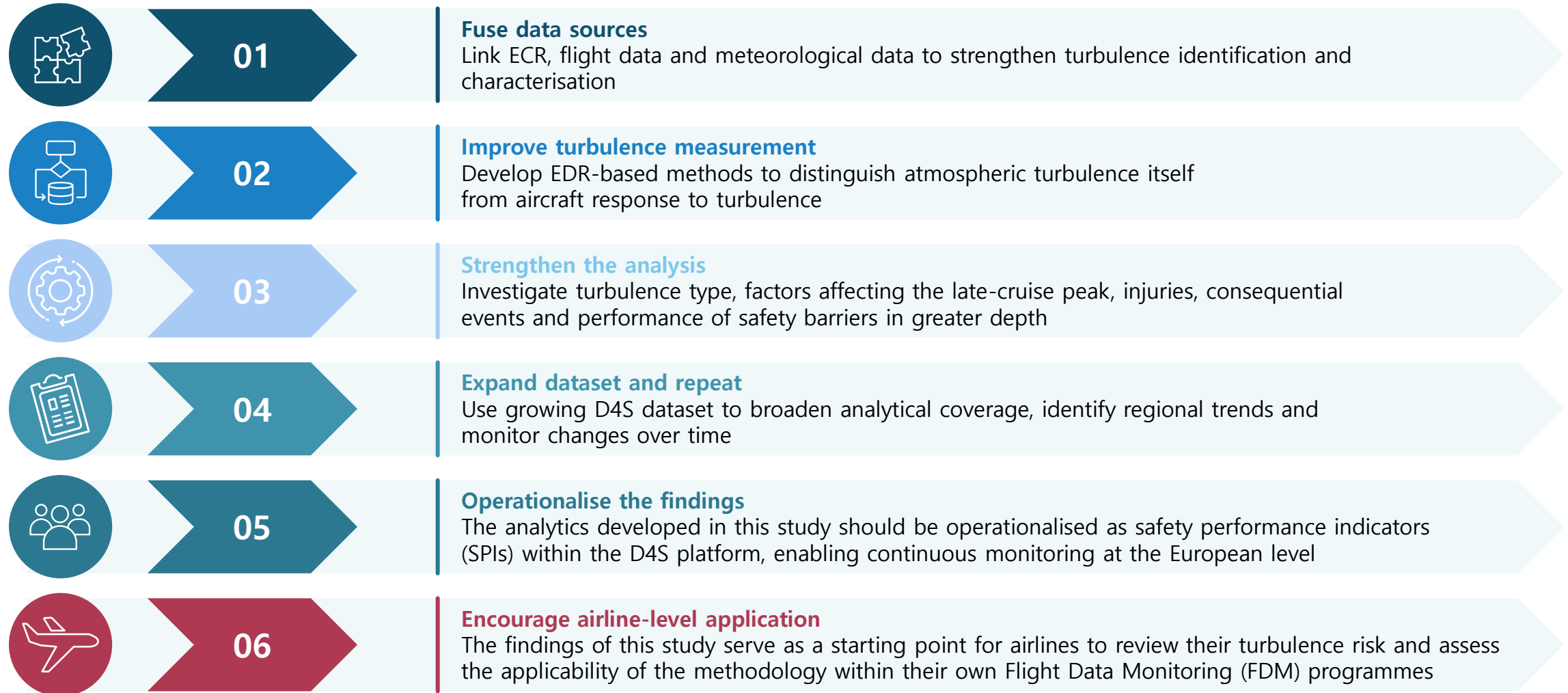


This study...

- ✓ Establishes a baseline analysis of turbulence, enabling **future changes** in turbulence to be **monitored and tracked** over time
- ✓ **Supports evidence-based safety analysis** and decision-making through a comprehensive analysis of turbulence

* General sources: EASA Scientific Committee Annual Report 2025, European Plan for Aviation Safety (EPAS) 2023-2025, IPCC Sixth Assessment Report (AR6)
¹ Lee, Williams & Frame (2019), *Nature*; Storer, Williams & Joshi (2017), *Geophysical Research Letters*
² Rädler, Groenemeijer, Faust, Sausen & Púčik (2019), *npj Climate and Atmospheric Science*

Way forward





Q&A

Questions?

For sending questions and comments, please use the Slido app or join directly through the website:

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A square QR code with a white background and black pixels, used for quick access to the Slido session.

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A white icon on a dark blue background consisting of two overlapping speech bubbles. The top bubble contains a question mark, and the bottom bubble contains an exclamation mark.

Feedback



**Which aspect of turbulence
would you like to
understand better?**

In view of future R&D

**Join at
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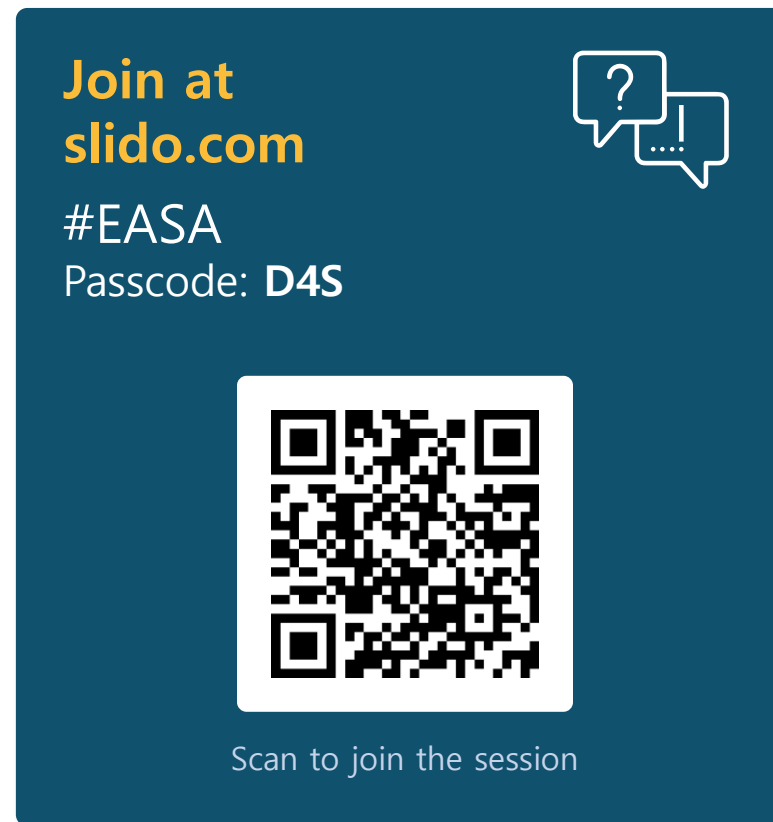
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Feedback



How relevant was the
content covered today to
your work or interests?

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Collaboration and data sharing enable safety research



Multi-modal turbulence identification

Combining **ECR narratives and recorded flight data** to capture both reported events and measured aircraft response, which has allowed for a **broader view on turbulence**



Unprecedented data volume and diversity

Enabling a **first-of-its-kind**, large-scale European turbulence study based on **data from multiple operators**



From research to monitoring

Paving the way towards a **data-driven** European safety monitoring framework



Interdisciplinary expertise

Bringing together **EASA safety expertise, NLR scientific and operational expertise** and **ALG data analytics/AI capabilities** within a European research framework



Supported by



The collaboration between ALBATROS and D4S unlocks unprecedented data-driven aviation safety research on in-flight turbulence at European scale



Co-funded by
the European Union



ALBATROS Project

Directed study on in-flight turbulence

Thank you



In collaboration with:



EASA

ALG

More about the project: www.albatros-horizon.eu

Selection of exposure data

Three candidate exposure datasets were evaluated:

	Data Volume	Temporal Scope	Regional Scope	Overflight Coverage	ECR Coverage	Conclusion
ECTRL	57M flights	'19-'25	EASA MS*	Yes	>95%	Best trade-off
ADS-B	101M flights	'24-'25	Worldwide	No (Possible)	83% (Up to 100%)	Limited temporal scope
Eurostat	Variable	Variable	EASA MS*	No	90%	Lack of overflights

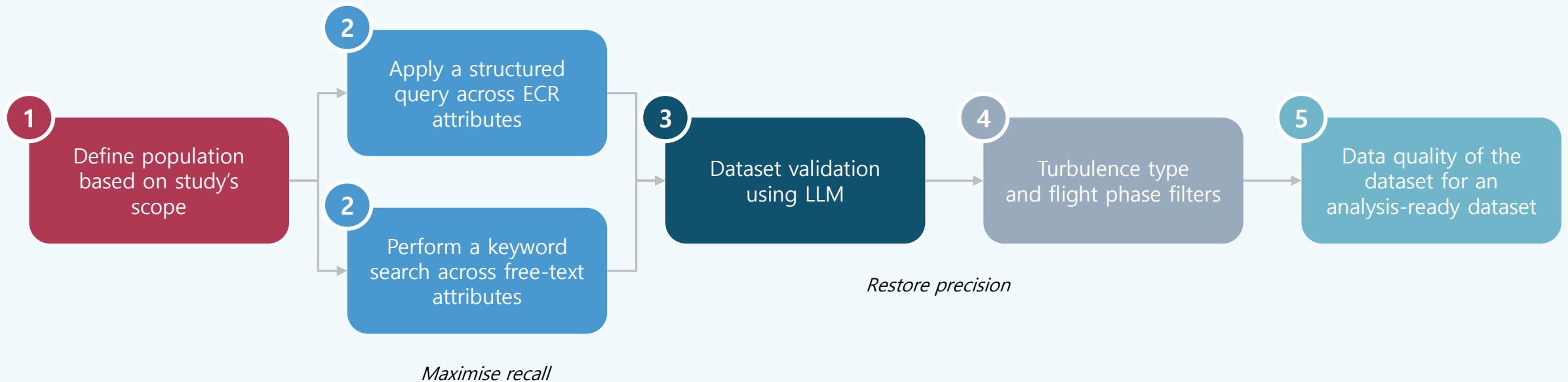


EUROCONTROL

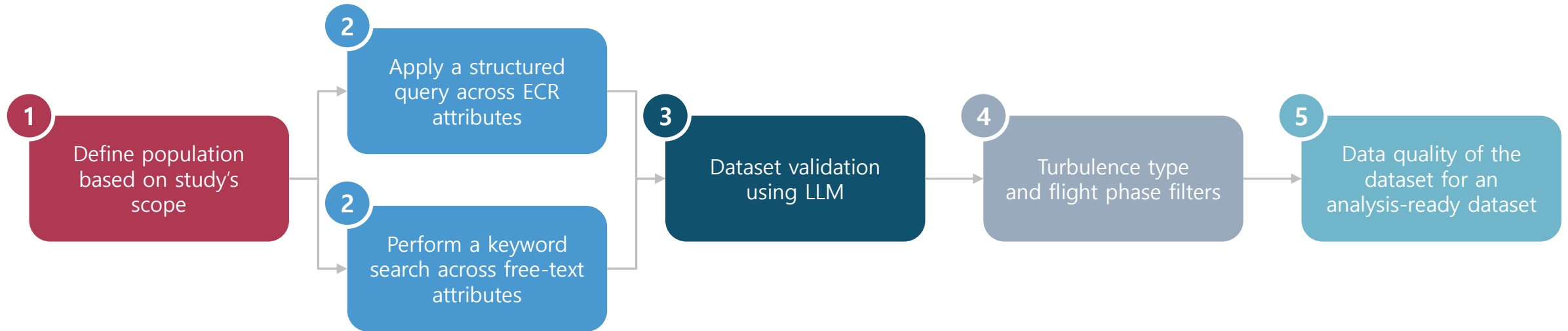
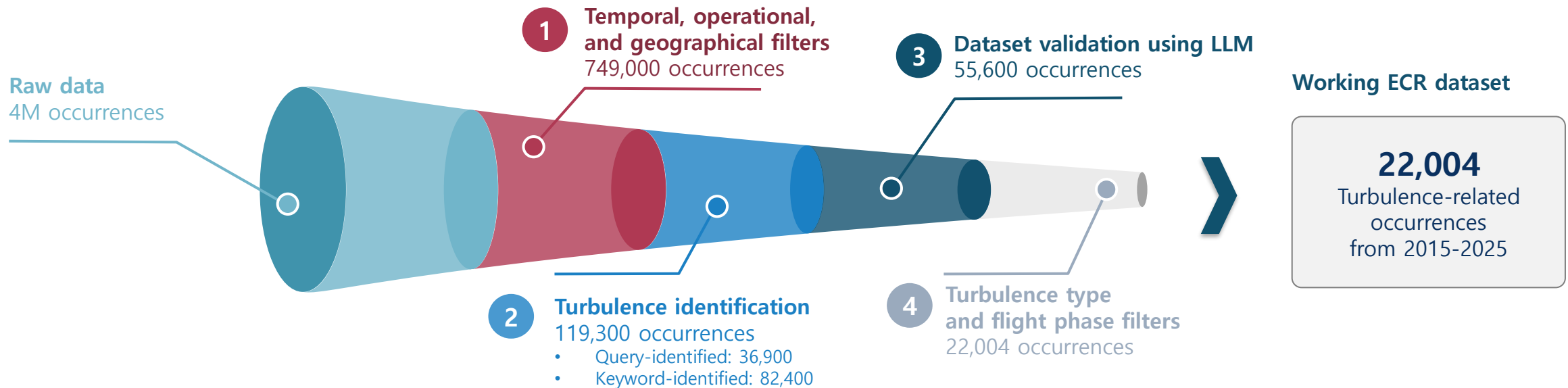
offered the best trade-off with **excellent ECR coverage**, **adequate temporal scope**, and the inclusion of **overflights**

* Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Latvia, Lithuania, Liechtenstein, Luxembourg, Malta, Netherlands, Norway, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, Switzerland

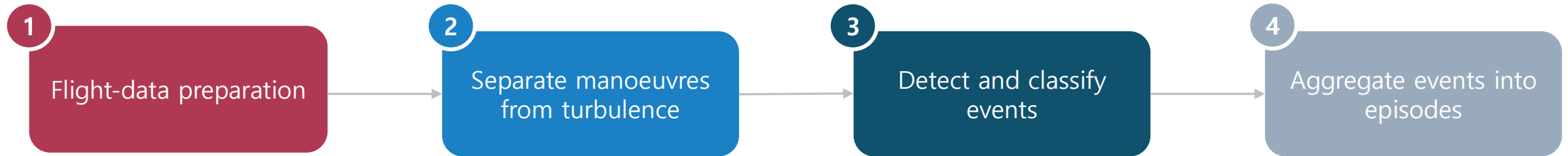
ECR turbulence identification methodology



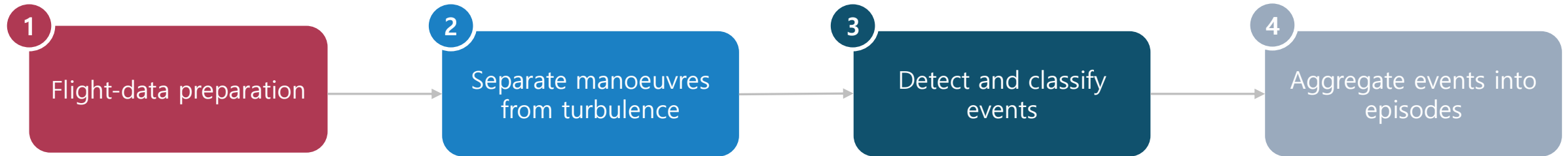
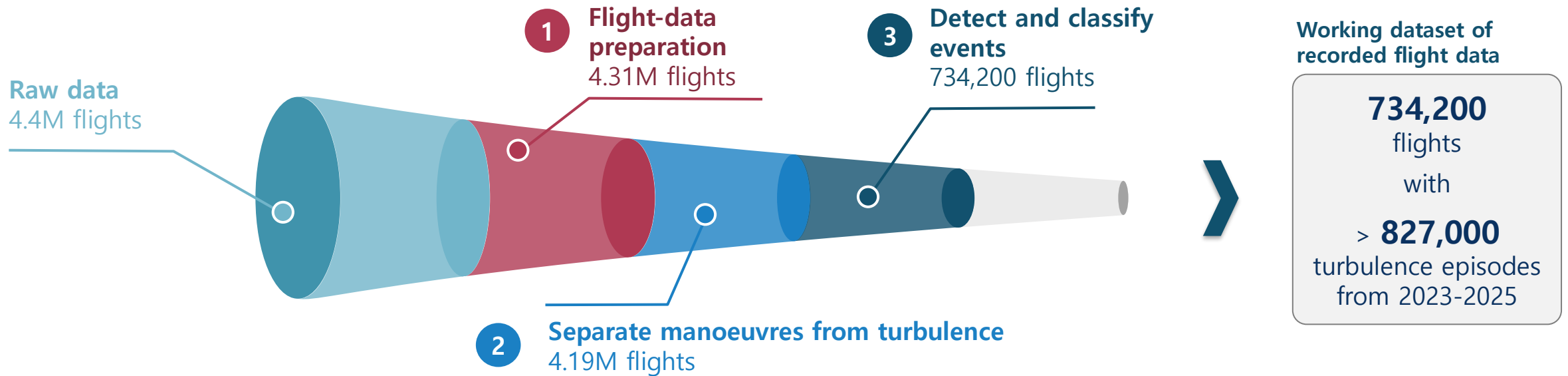
ECR turbulence identification methodology



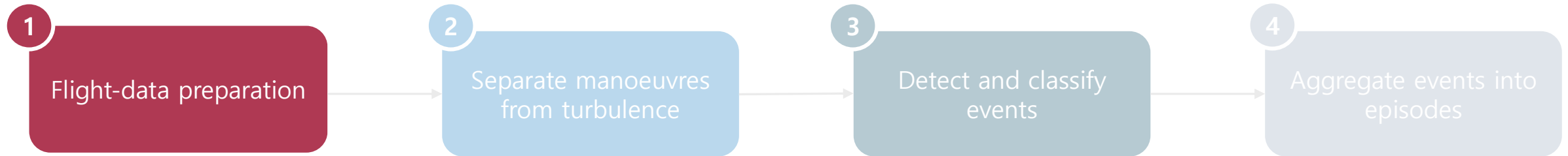
Recorded flight data turbulence identification methodology



Recorded flight data turbulence identification methodology



Recorded flight data turbulence identification methodology



01

QUALITY FILTERS

Only valid operational flights are retained

02

FLIGHT VALIDATION

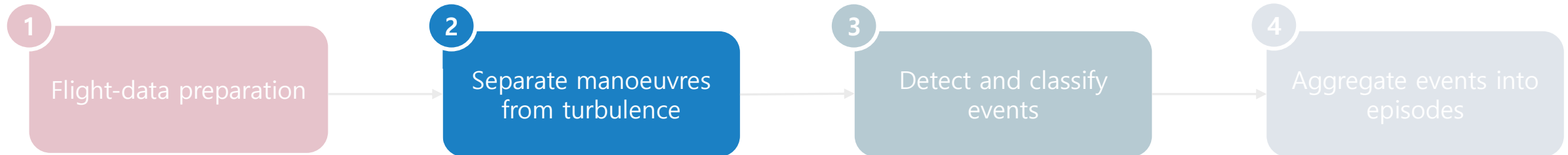
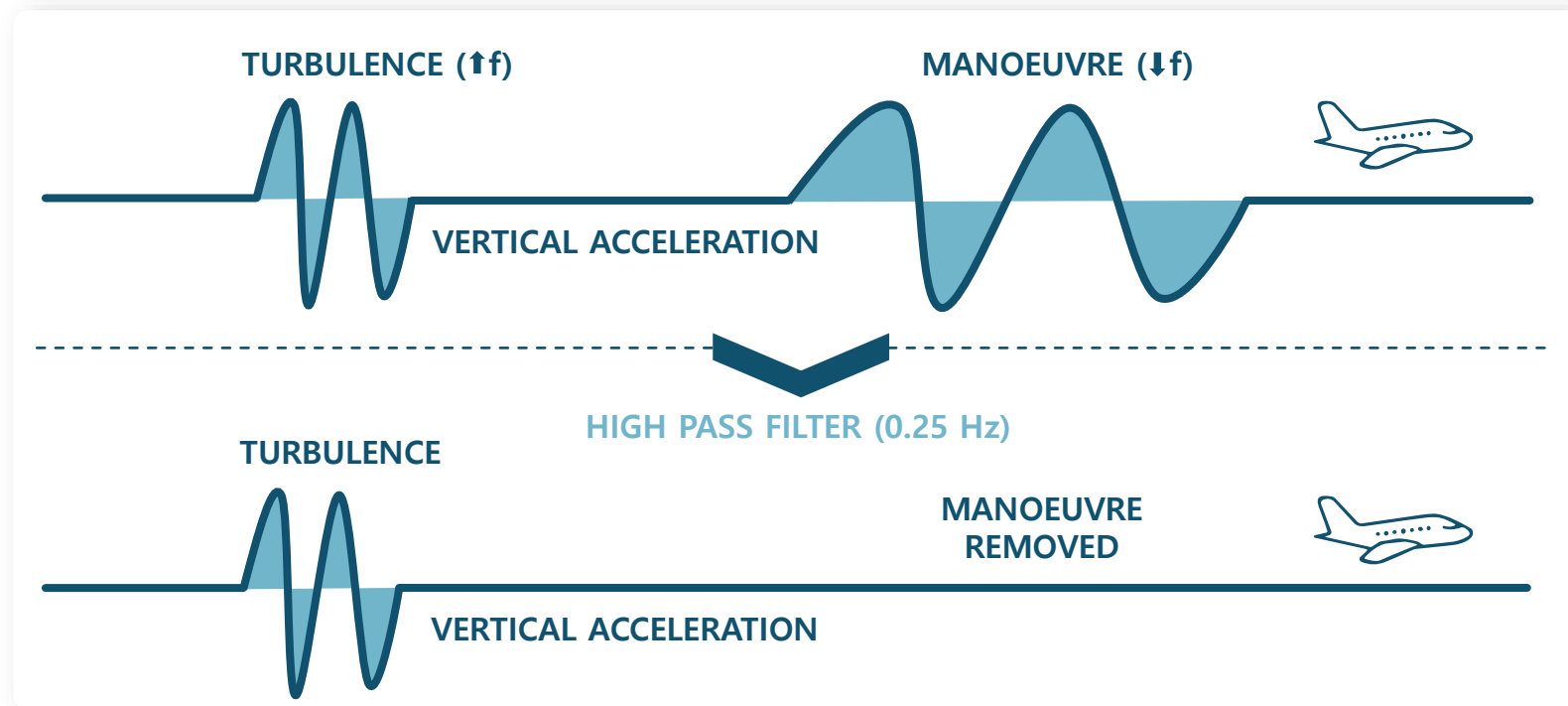
Flights must contain a complete airborne phase and the data required for analysis

03

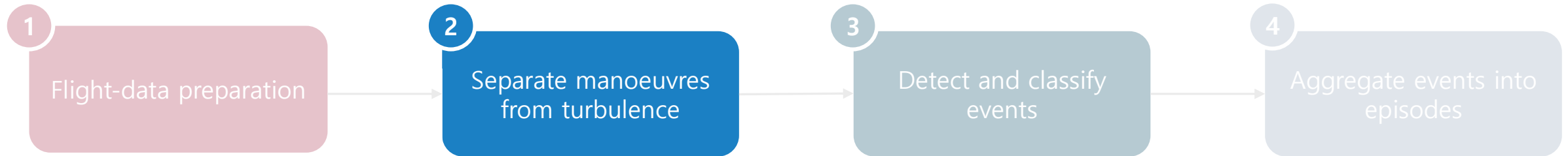
BIAS CORRECTION

A small systematic offset can affect accelerometer measurements. The bias is estimated during stable flight and corrected throughout the flight

Recorded flight data turbulence identification methodology

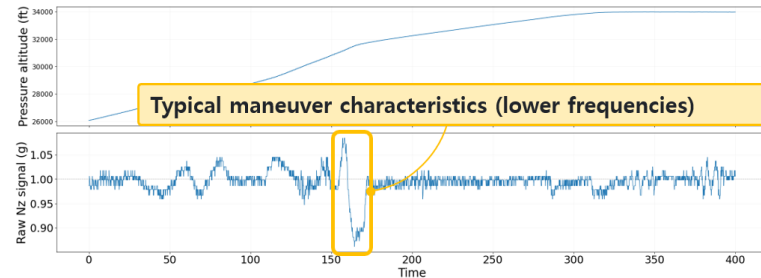


Recorded flight data turbulence identification methodology

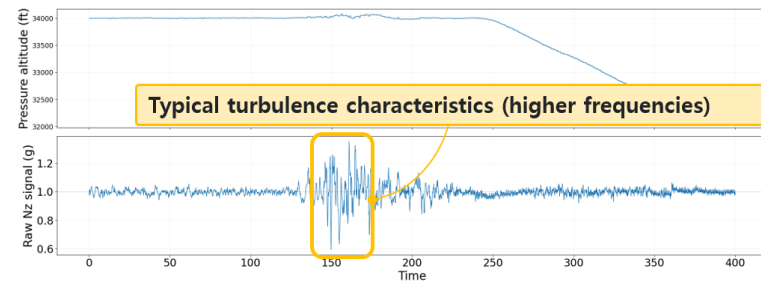


Manual identification

Flight #1



Flight #2



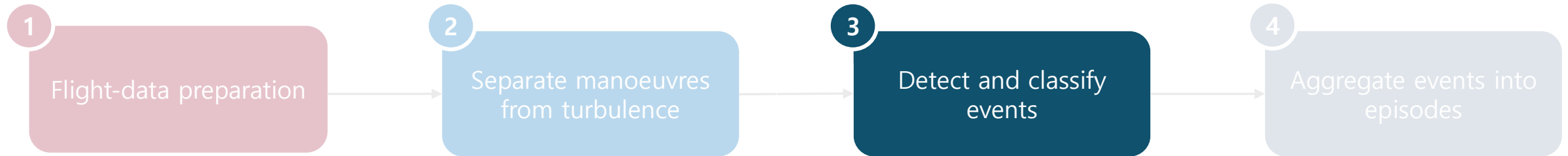
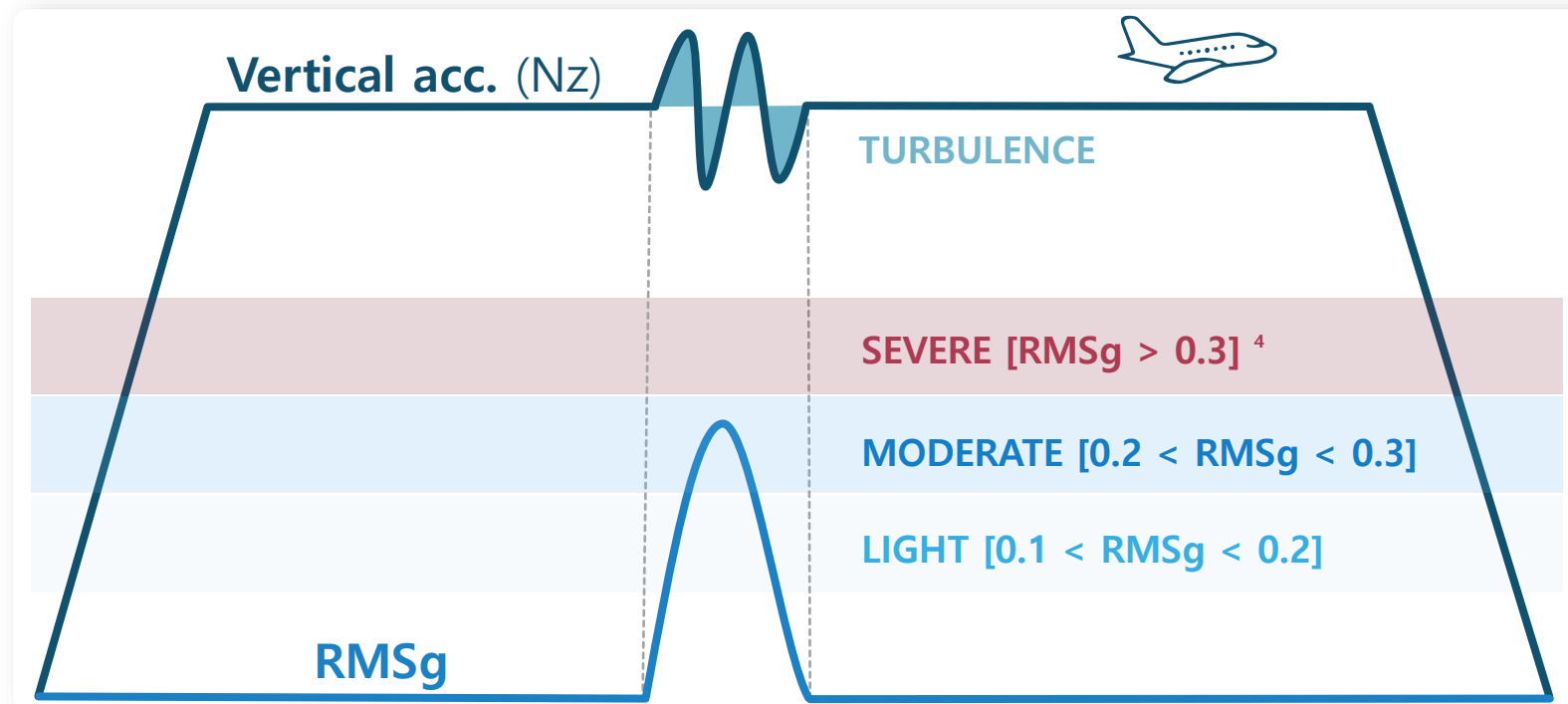
Average frequency* [Hz]	
Manoeuvres	0.05
Turbulence	0.48



High pass filter (0.25 Hz)

* The average frequency is calculated based on a random sample for both groups

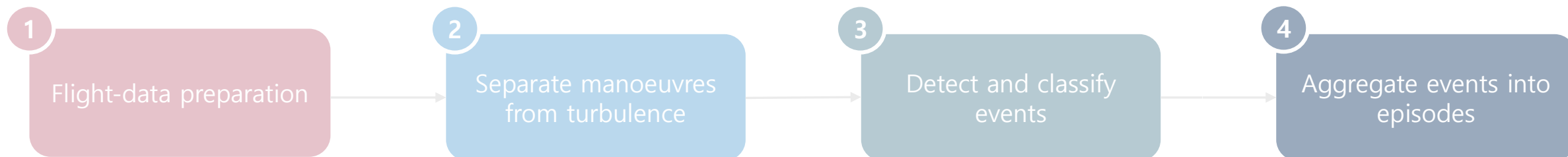
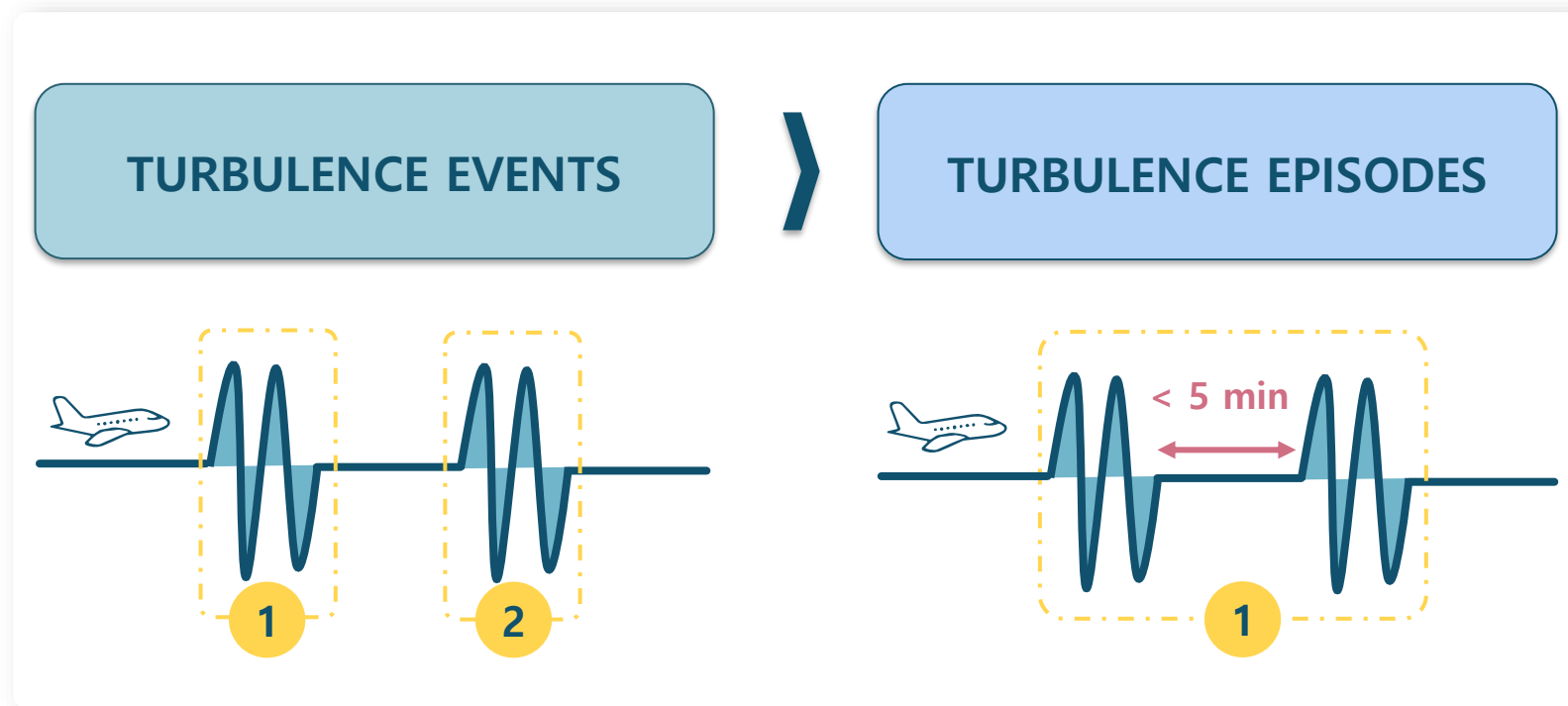
Recorded flight data turbulence identification methodology



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

⁴ Airborne Turbulence Detection System Certification Tool Set (Hamilton & Proctor, 2006)

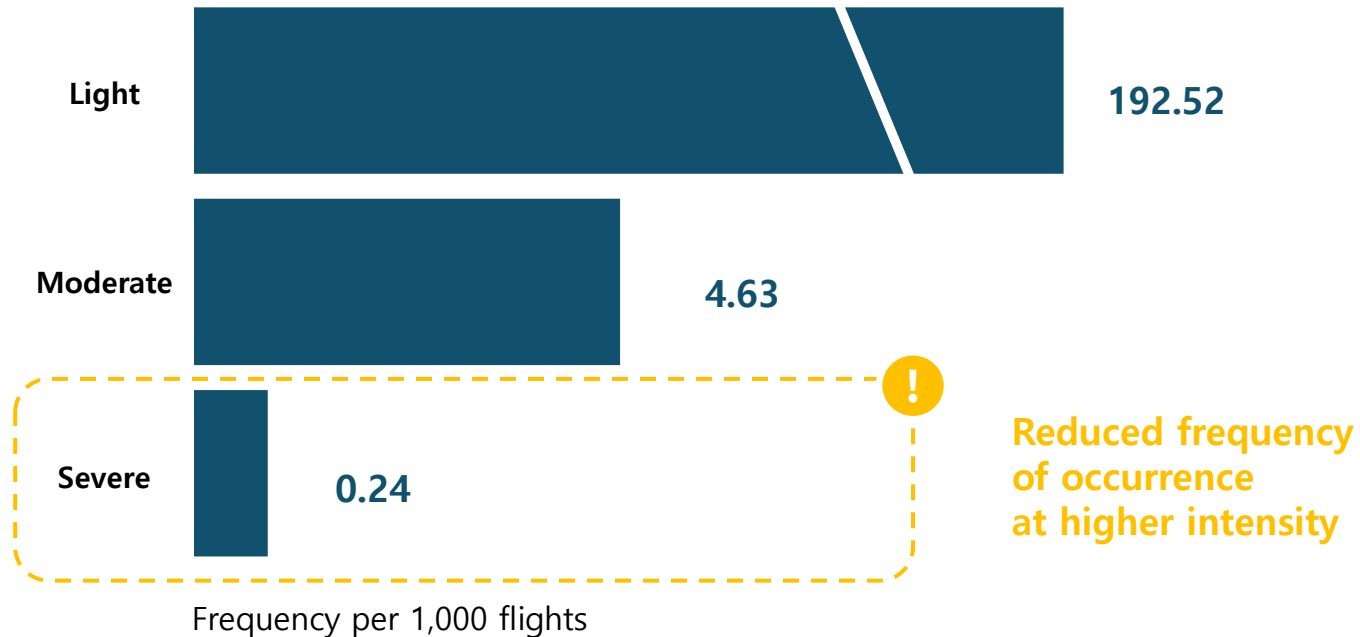
Recorded flight data turbulence identification methodology



When physical and reported exposure converge

Physical exposure to turbulence by intensity level

Recorded flight data



Frequency of reported turbulence ECR data

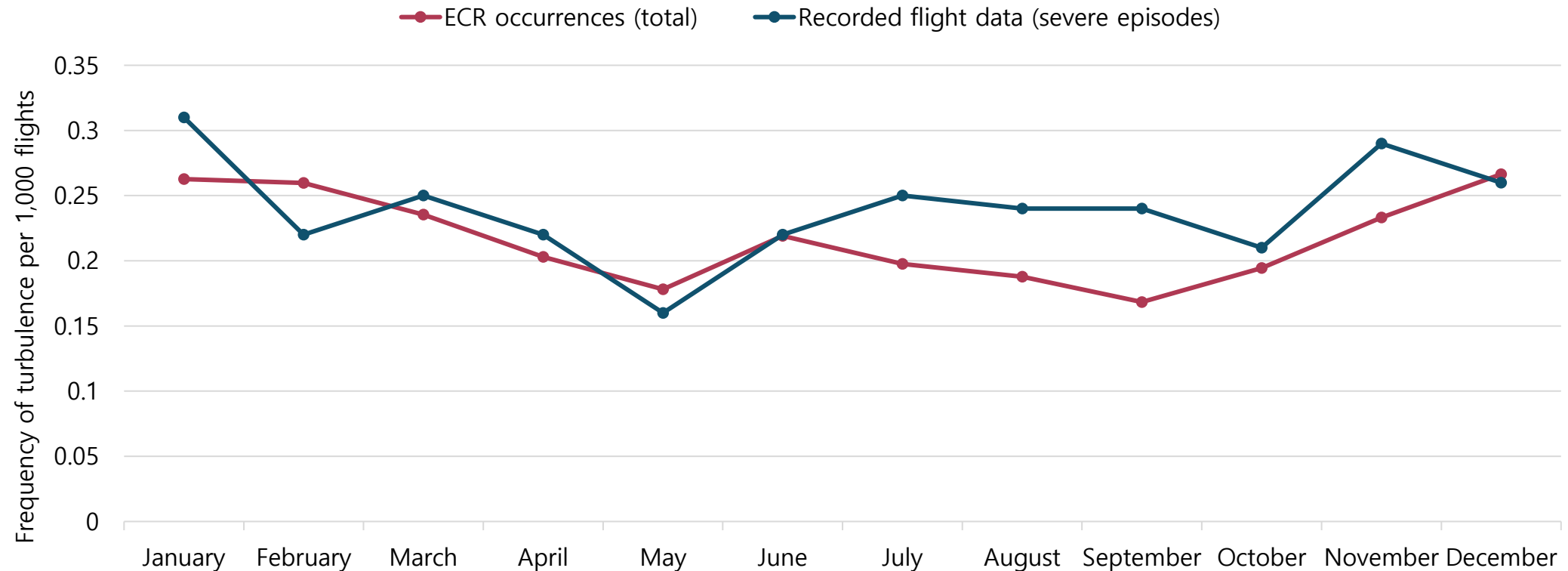
0.28

turbulence occurrences
per 1,000 flights

Higher intensity reveals consistent seasonality

Seasonal distribution of turbulence encounters per data source

Recorded flight data & ECR data



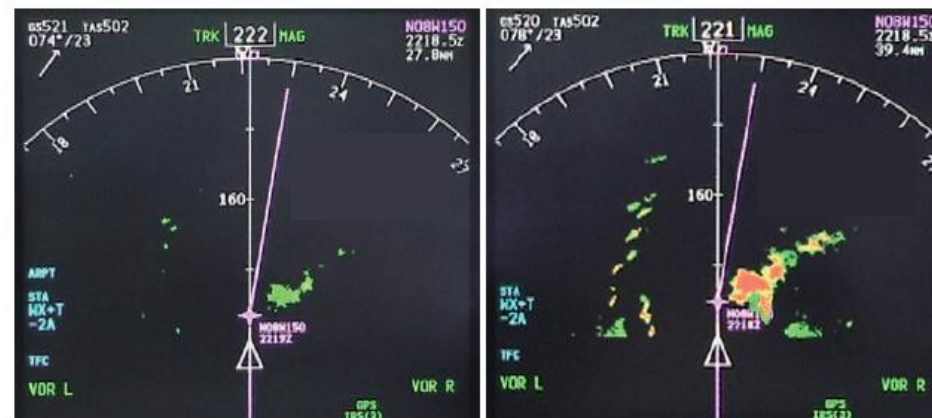
On-board weather radar and late-cruise peak (1/2)

Traditional / manual radar

- **Manual antenna tilt and gain management**
Crew must adjust the radar settings as altitude, range and flight phase change to maintain an effective scan ahead.
- **Greater crew workload during descent**
Maintaining appropriate coverage requires active radar management, particularly as the aircraft transitions from high-altitude cruise to lower-altitude flight.
- **More limited high-altitude weather detection**
Cold, high-altitude convective cells can become less reflective, making some weather more difficult to detect without appropriate gain management.

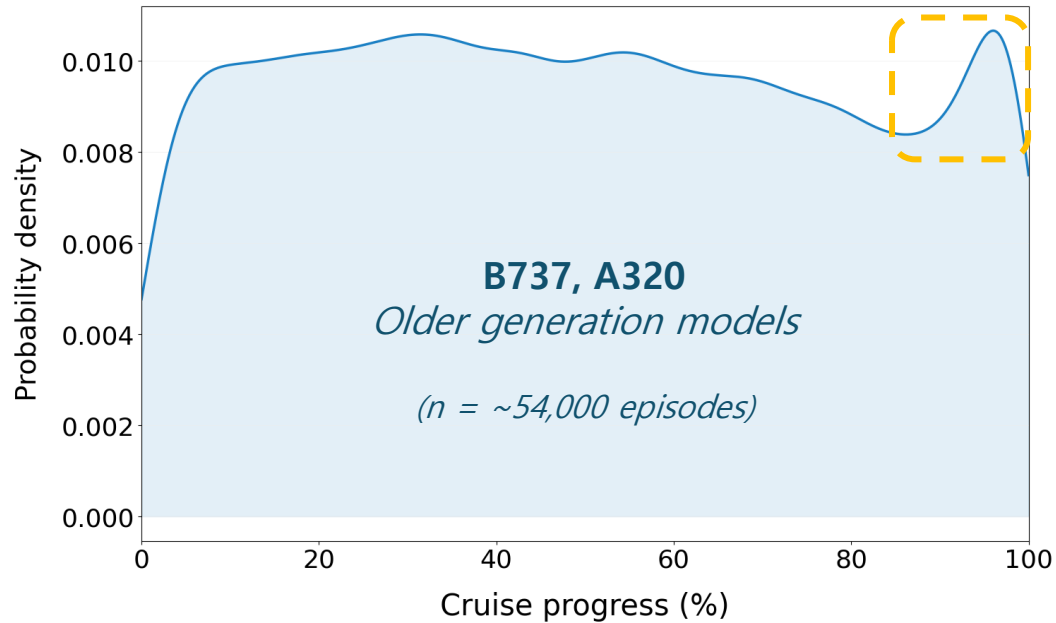
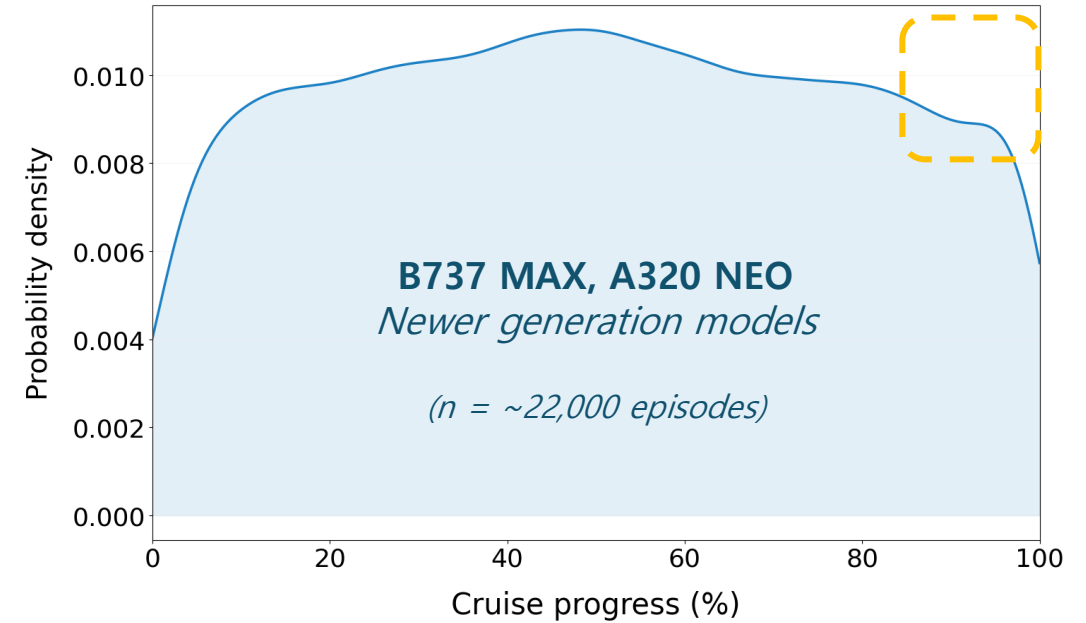
Modern multiscan / automatic radar

- **Automatic tilt and gain management**
Radar systems can automatically adapt scanning and sensitivity based on aircraft altitude, range and other operating conditions
- **3D / multi-angle scanning**
Multiple scans can be combined to build a more complete picture of weather ahead, reducing reliance on a single manually selected antenna angle
- **Temperature-based gain compensation**
Modern systems can increase sensitivity at high altitude to account for reduced radar reflectivity associated with ice-crystal-dominated convection
- **Reduced reliance on manual radar management**
Automation aims to maintain effective weather detection while reducing the crew workload associated with continuously adjusting radar settings.



Illustrative example only: radar displays and capabilities vary by aircraft, system and operator; the figure is intended solely to illustrate the general differences discussed above

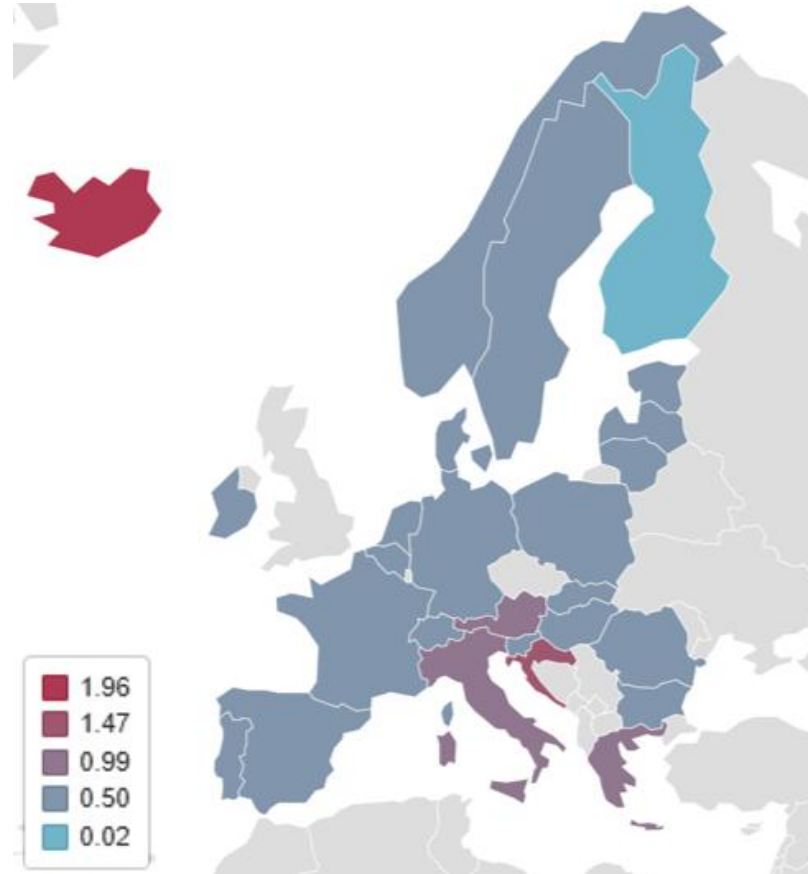
On-board weather radar and late-cruise peak (2/2)



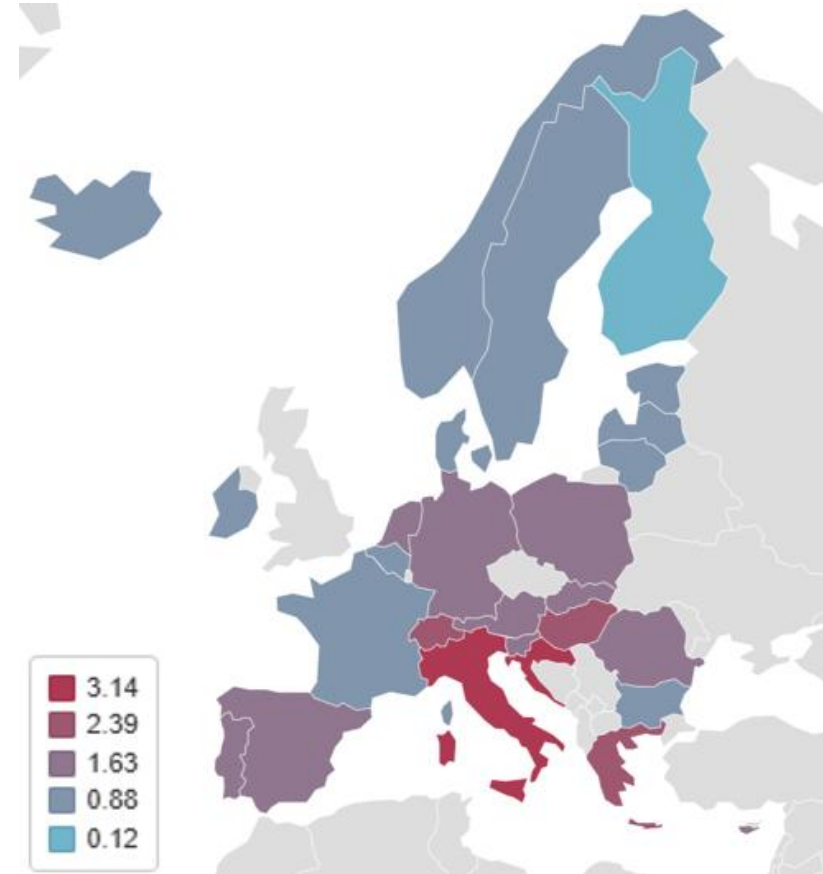
- ✓ Aircraft type used as a **proxy** for the actual radar weather installation
- ✓ **Same data processing** for both generations
- ✓ **Large sample sizes:** 54,000 and 22,000 turbulence episodes during cruise, respectively

Geographical distribution

Clear air turbulence occurrences
ECR data



Convective turbulence occurrences
ECR data

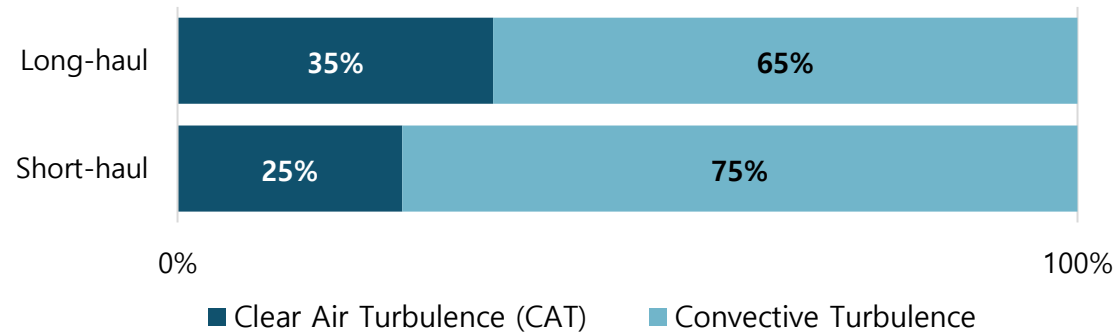


Note: Normalisation is done per 1,000 occurrences reported in each state

Short vs. long-haul operations

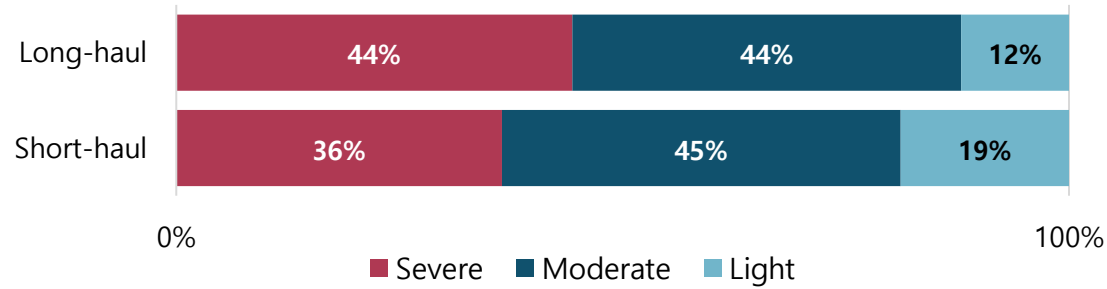
Turbulence type by route type

ECR data



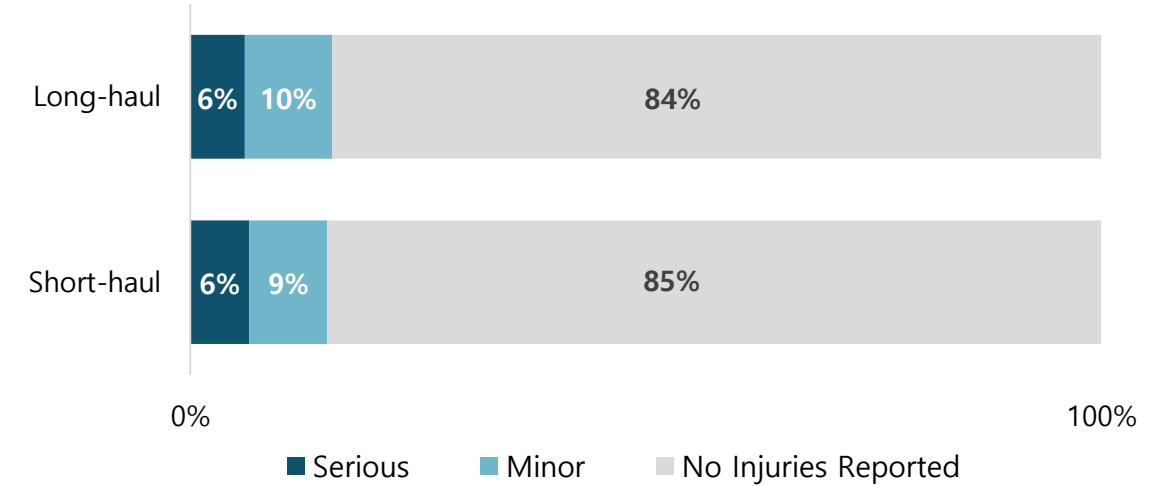
Intensity level by route type

ECR data



Injury severity level by route type

ECR data

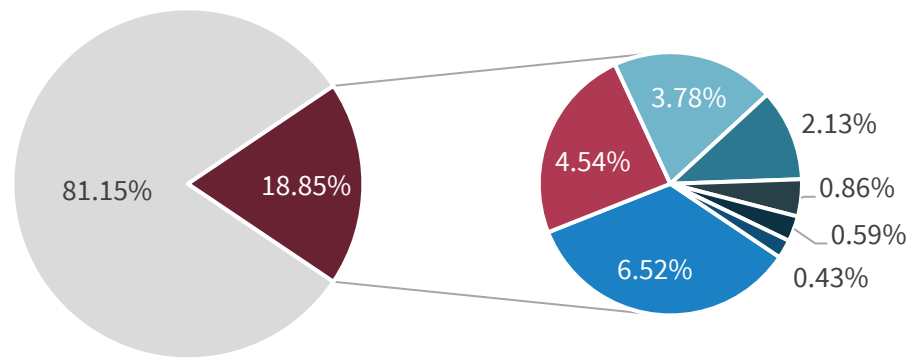


67%
of turbulence-related occurrences
are short-haul flights

Injury location

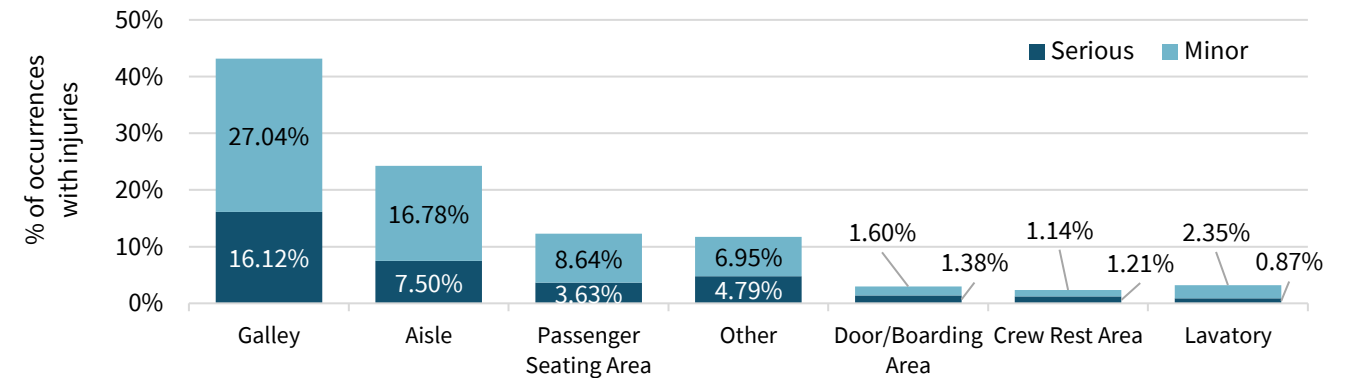


Injury location ECR data

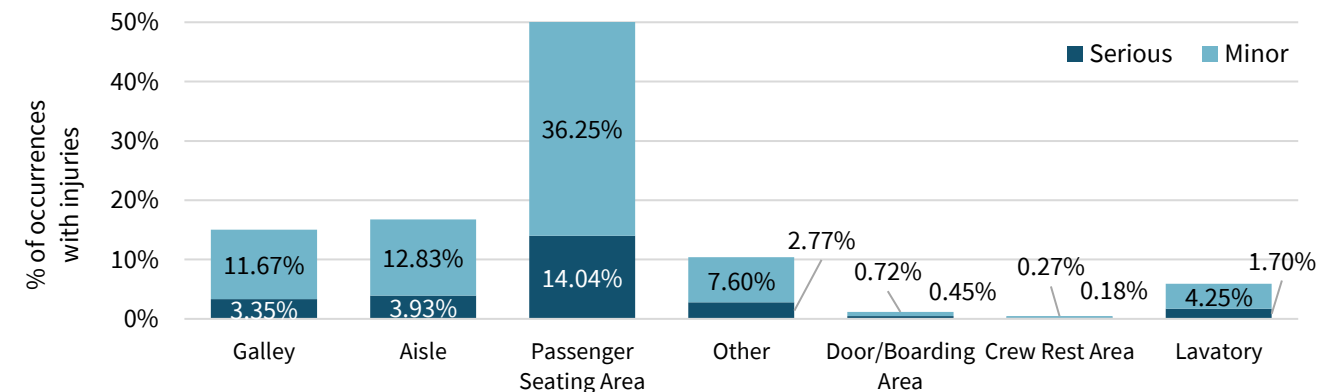


- Not Reported
- Passenger Seating Area
- Other
- Door/Boarding Area
- Galley
- Aisle
- Lavatory
- Crew Rest Area

Cabin crew: Injury location ECR data



Passengers: Injury location ECR data

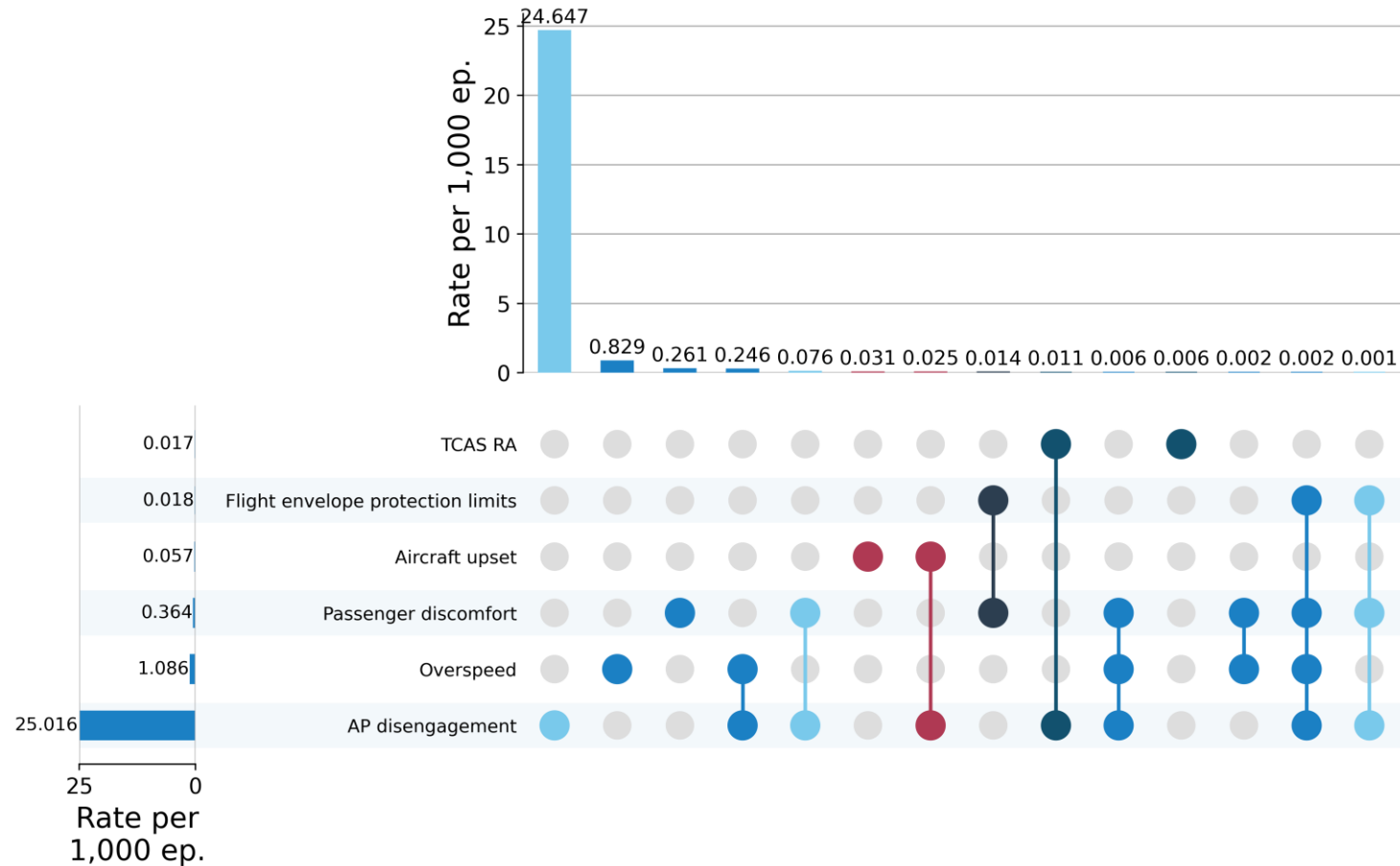


Consequential events



Rate of consequential events by 1,000 turbulence episodes*

Recorded flight data



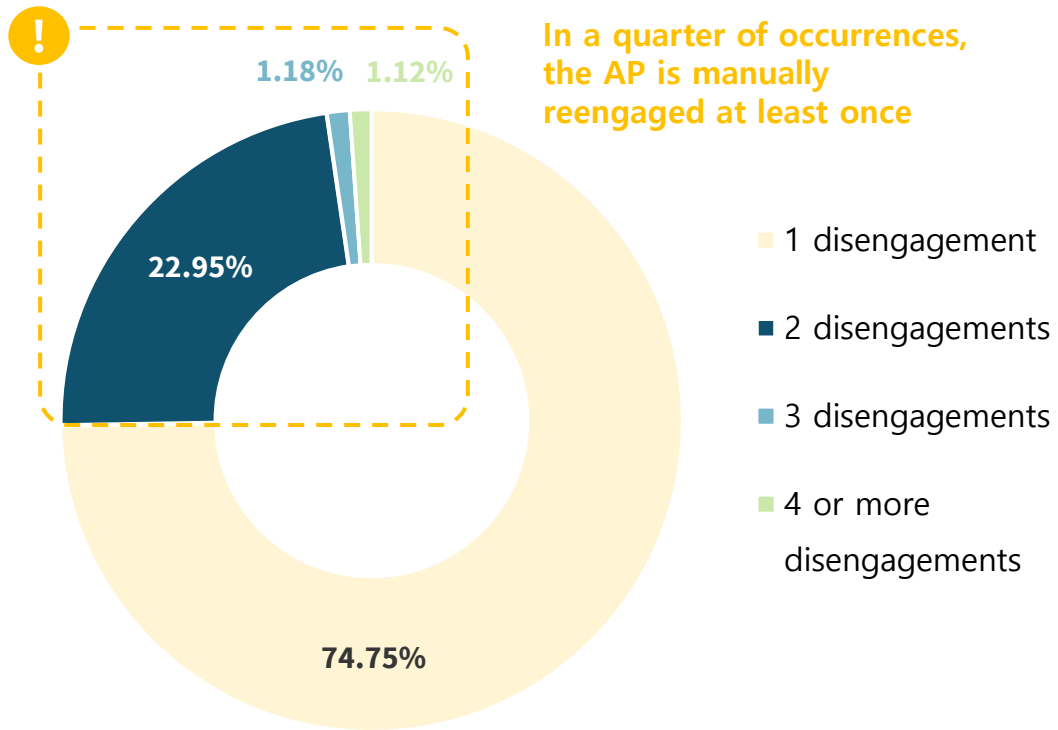
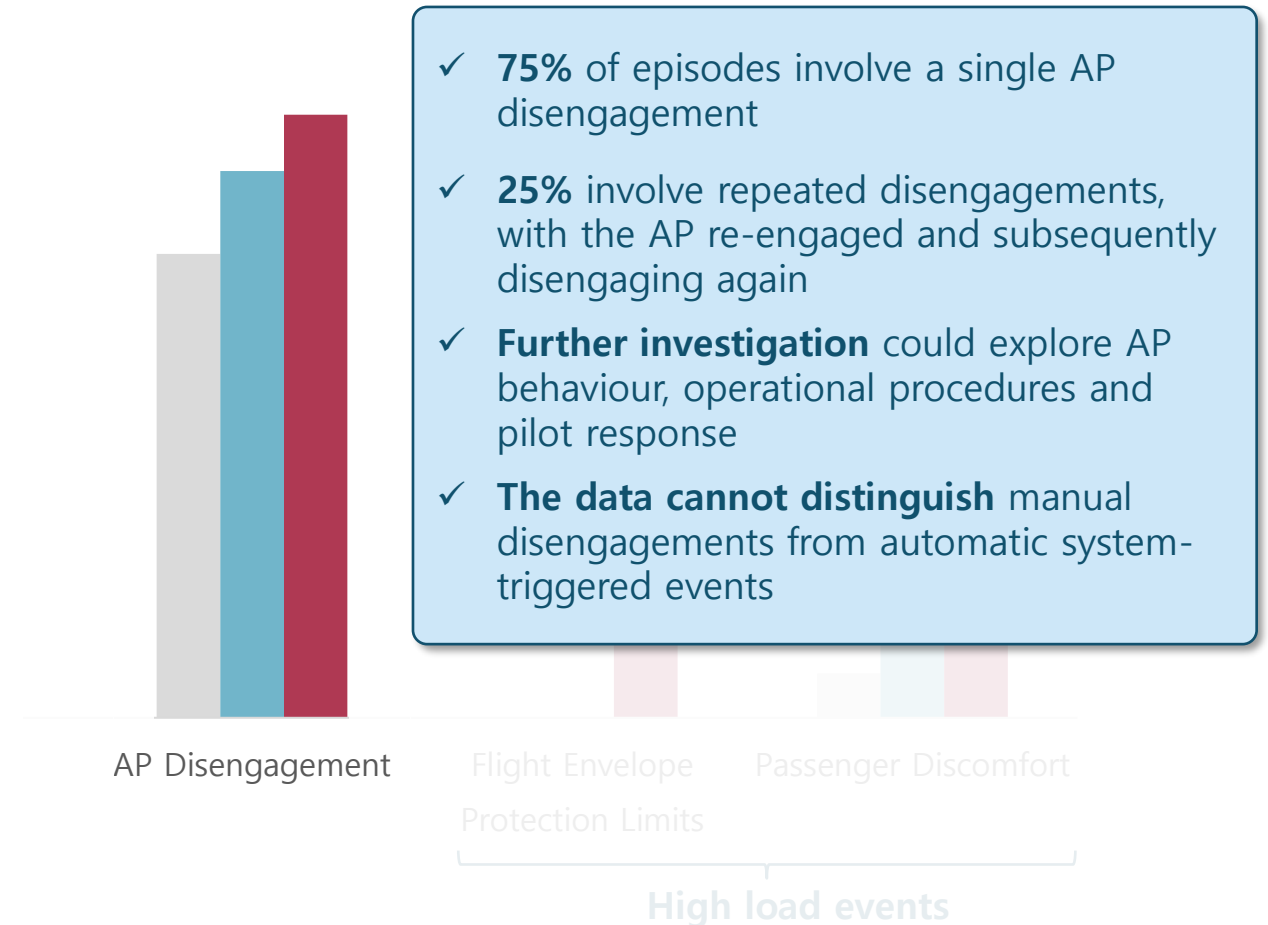
* Vertical bars show rates of combined consequential events, bars on the left show aggregated rates per consequential type

Autopilot disengagements



Breakdown of autopilot disengagements by number of disengagements

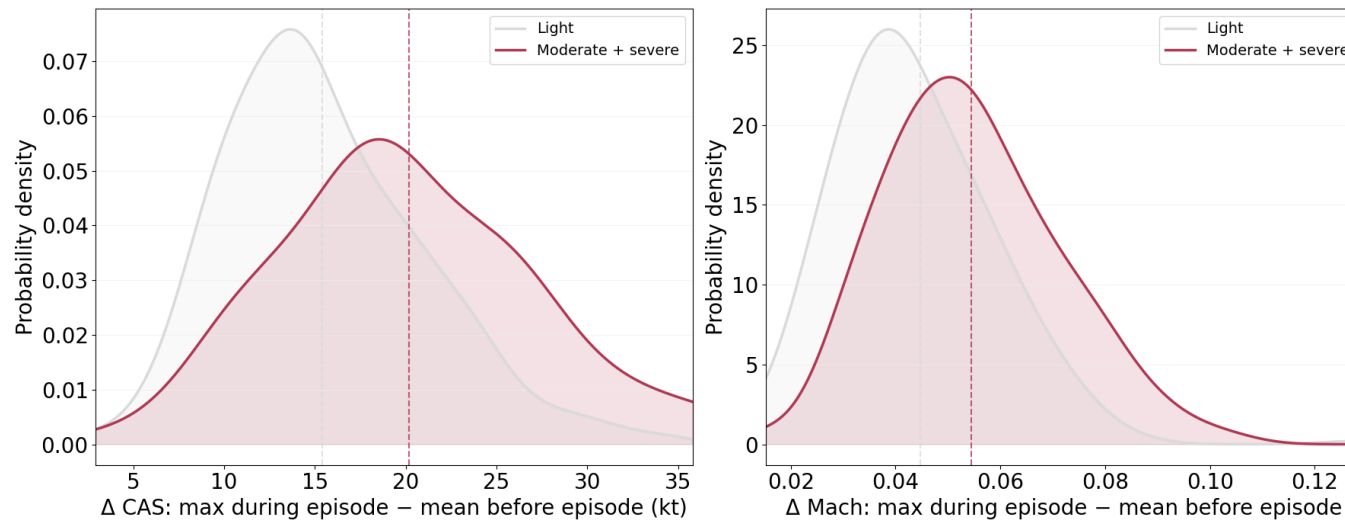
Recorded flight data



Overspeed events

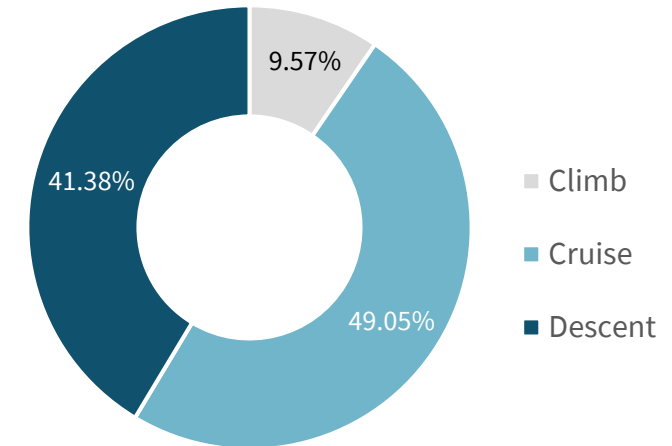
Increase in calibrated airspeed (CAS) and Mach number in overspeed events

Recorded flight data



Breakdown of overspeed events by flight phase

Recorded flight data



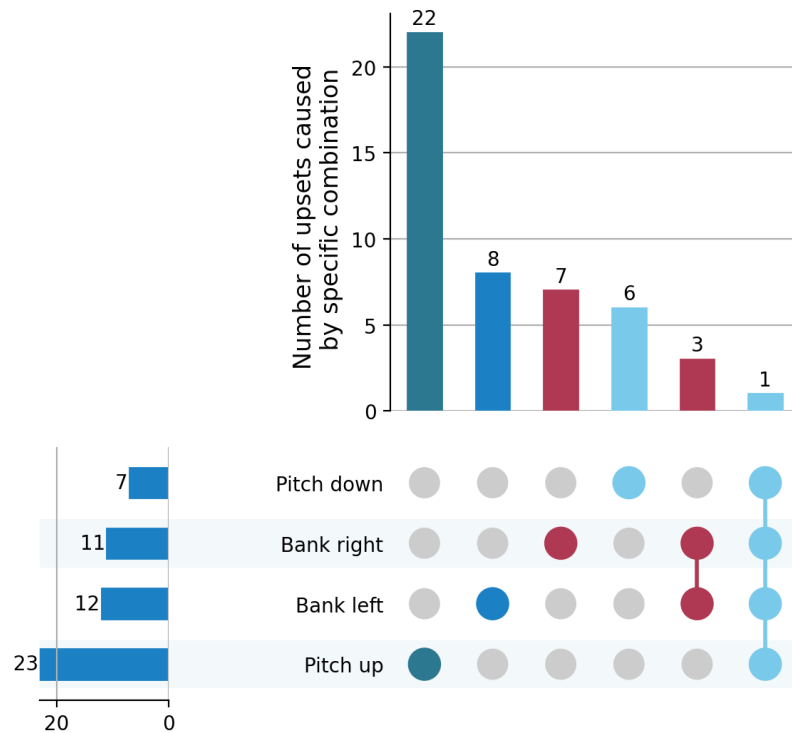
N = 899
detected overspeed events

Aircraft upsets



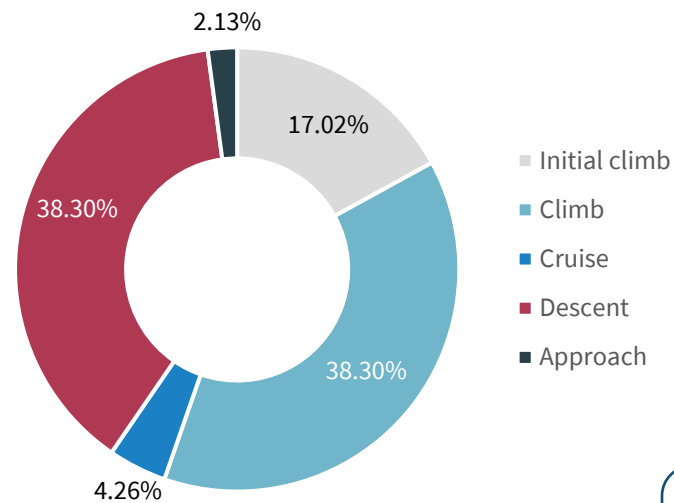
Types of aircraft upset**

Recorded flight data



Breakdown of aircraft upsets by flight phase

Recorded flight data



Aircraft upset bounds*

	Roll	Pitch
Aircraft Upset	> 45°	> 25° or < -10°

* Based on EASA and FAA definitions

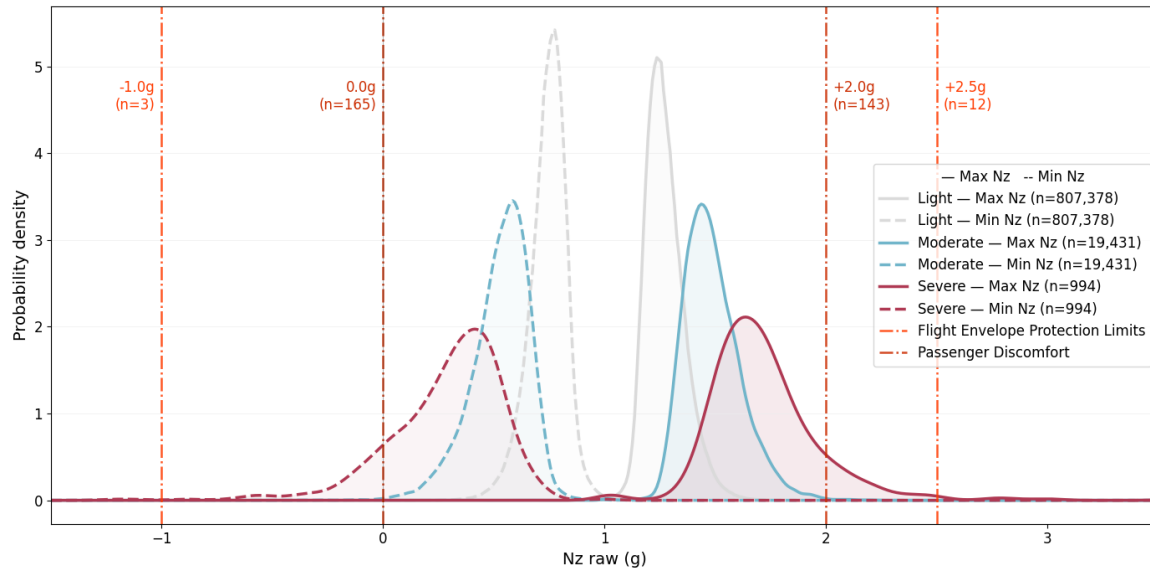
* Vertical bars show number of upsets caused by each combination of attitude excursion. Lateral bars show total number of upsets by type of aircraft upset

Extreme load events



Probability density of the minimum and maximum Nz value by intensity*

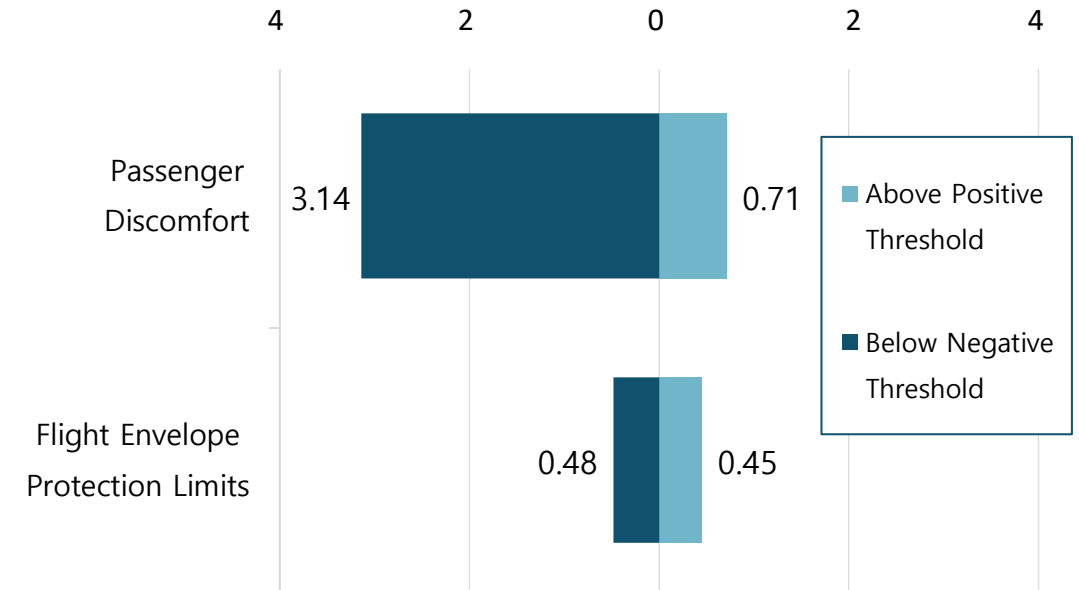
Recorded flight data



	Lower Bound	Upper Bound
Passenger Discomfort	$g < 0$	$g > 2$
Flight Envelope Protection Limits	$g < -1$	$g > 2.5$

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

Recorded flight data



* Vertical bars show the four extreme load thresholds

Limitations



ECR safety occurrences

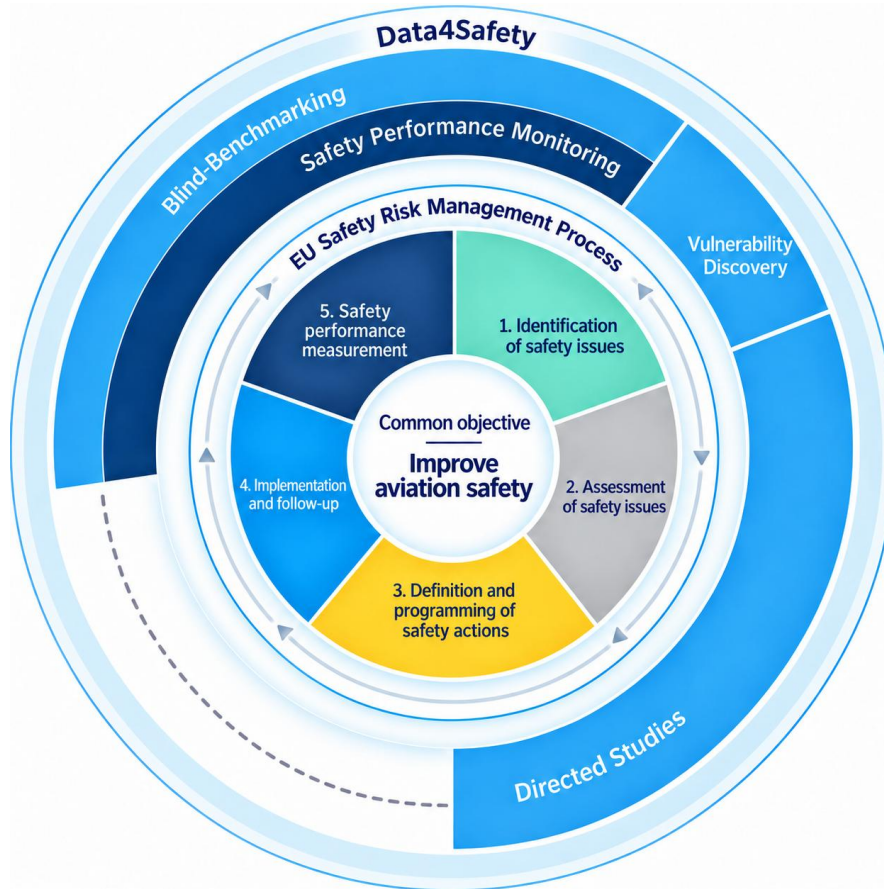
- **Subjectivity in reported turbulence intensity and type**
(consequences, individual reporting biases)
- **Incomplete taxonomy fields and narrative information**
- **Uncertainty in automated classification and data enrichment**
Over 99% agreement on manual validation, but no systematic validation
- **Reported consequences cannot always be attributed solely to turbulence**
Other contributing factors limit causal interpretation
- **Limited representativeness of the ECR sample**
Broad European coverage, not representative of all regions/operators



Recorded flight data

- **Limited representativeness of the recorded flight data sample**
Overwhelmingly short-haul, narrow-body operations
- **Intensity represents aircraft response rather than atmospheric turbulence** (RMSg is not an aircraft-independent measure of atmospheric turbulence)
- **Absence of meteorological context** prevents reliable classification of turbulence type and independent validation of meteorological mechanisms
- **Limited availability of aircraft parameters**
Lack of control-surface deflections, angle of attack, and pilot inputs limit the analysis of consequential events
- **Potential overlap between turbulence and aircraft manoeuvres.**
High-pass filtering may not be able to fully separate turbulence-induced acceleration from residual manoeuvre-related dynamics

The EU Safety Risk Management (SRM) Process



Analytical outputs from D4S and/or related research studies **naturally connect with EU SRM steps**, but defining the **interaction model** is key to clarifying how both processes contribute and interact

By leveraging multi-source data, studies can generate evidence on **exposure**, **precursors** and **barrier performance** to support EU SRM assessment and monitoring, making a defined interaction model key to structuring this contribution

The ALBATROS directed study on in-flight turbulence represents a **practical application** of how Data4Safety and research activities can complement the EU Safety Risk Management process, **delivering the evidence and analysis** required for the assessment of the safety issue addressed in Step 2 of the process