01

point one

NABLA Mobility

white paper

Better Strategies for Turbulence Avoidance: Optimizing Altitude for Improved Safety and Fuel Efficiency

1. Executive Summary

Despite the common understanding that there will always be a tradeoff between safety and efficiency, airlines are now able to increase safety while simultaneously improving fuel efficiency by up to 5% during the cruise phase. This is made possible by utilizing precise, dynamic turbulence predictions and multi-objective optimizations.

Turbulence is the leading cause of safety incidents for airlines, accounting for 37% of all recorded incidents in the United States (a broad measure that includes ground, cabin and runway incidents). Consequently, turbulence is the direct cause of significant additional costs: insurance expenses, delays and fuel. Traditional methods of navigating turbulence are largely dependent on pilots' intuition, backed up by training and accumulated experience. This is ultimately due to a limitation of the granularity of turbulence data that is available to pilots with current technology.

By introducing multi-disciplinary techniques, we have improved upon current turbulence prediction performance by between 7x and 14x. Passing this new level of granular information to a custom, advanced multi-objective (safety, fuel, time, etc.) optimization system, enables us to make altitude based path recommend-ations that provide pilots with high resolution information needed to make effective decisions.

This combination of advanced ML allows us to affect the outcomes of the flight: simultaneously enhancing safety and reducing fuel consumption by up to 5%. Furthermore, the solution can be integrated into existing workflows with minimal investment, without requiring a significant increase in crew workload.

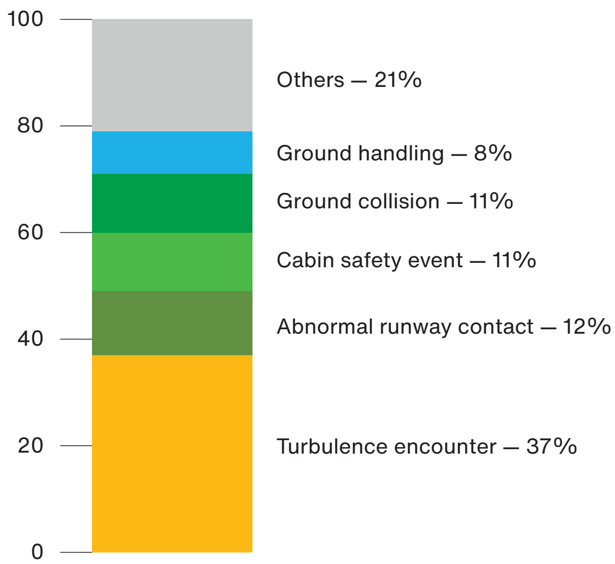
Additionally, numerous academic studies indicate that turbulence will increase in frequency, magnitude, and volatility due to climate change. The category of severe turbulence is expected to increase most. This implies that despite the tremendous effort that both pilots and operations teams put into current safety and efficiency efforts, as the atmosphere becomes more energetic, the overall amount of turbu-lence will increase, intensity levels become more severe, and the efficacy of traditional avoidance methods will diminish.

These analyses lead us to conclude that the ability to locate and identify more turbu-lence with higher granularity, and subsequently map the path of least resistance through it, will become essential.

2. Issue

Turbulence induced accidents directly add significant costs to airlines. The current method of turbulence avoidance has the side effect of adding significant fuel costs, while cutting into decarbonization efforts. The root cause is a lack of granularity and turbulence types that are technologically capable of being represented in existing turbulence forecasting methods.

According to the National Transportation Safety Board, turbulence was the leading cause of aviation accidents in the United States from 2009 to 2018. As reported in the study ‘Preventing Turbulence-Related Injuries in Air Carrier Operations Conducted Under Title 14 Code of Federal Regulations Part 121’ those regularly scheduled commercial airlines, categorized as Part 121, are more likely to be involved in turbulence-related accidents.



Source: National Transportation Safety Board

Figure 1.

Number of turbulence-related accidents in the US (civil aviation operations from 2009 through 2018)

> *“Figure 1 shows the number of turbulence-related accidents involving different segments of US civil aviation operations from 2009 through 2018. During this period, there were a total of 197 turbulence-related accidents, accounting for 1.4% of all US civil aviation accidents. The involvement of turbulence in aviation accidents was not evenly distributed across operation types. However, turbulence was much more likely to be involved in Part 121 accidents than Part 135 or general aviation accidents, accounting for 37.6% of all Part 121 accidents during this period. There are many possible reasons for this, including the different operational environments, aircraft sizes, and the number and type of aircraft occupants typically involved in Part 121 air carrier operations compared with other aviation operations”*

> *"The accident data were obtained from the NTSB's Aviation Accident Database, and the flight activity data were obtained from the FAA. Most analyses summarize the 10-year period from 2009 through 2018; some analyses of accident trends are shown for the 30-year period from 1989 through 2018 to illustrate accident trends more clearly. These accident data were current as of September 24, 2020."*

Airlines incur numerous additional costs due to turbulence, the most pressing of which includes the safety and insurance of both passengers and crew members. Additionally, there are expenses due to increased fuel consumption due to the need to deviate from the most fuel-efficient altitude. This consequently demonstrates that turbulence events cause airlines to emit additional carbon dioxide.

> *"Turbulence can cost airlines anywhere from $250K to $2 Million dollars per year." (IATA)*
>
> *"Turbulence has consequences for the environment, by increasing aircraft fuel consumption and emissions of CO2, NOx, and other pollutants. According to Delta Air Lines and NASA, up to two-thirds of flights deviate from the most fuel-efficient altitude due to turbulence, for an average of 41 minutes per deviation.*
>
> *These deviations waste fuel — up to 160 million gallons annually — and they also contribute to climate change through 1.5 million tonnes of unnecessary CO2 emissions annually, equivalent to the annual emissions of 324,000 cars." (Impact case study (REF3), Prof. Paul D. Williams, University of Reading)*

Pilots and operations teams are forced to contend with a complex decision-making process (balancing safety, passenger comfort, on time performance, fuel, current altitude, traffic, etc) while only having a coarse understanding of where turbulence may or may not be. Currently, their best tool is PIREPs (pilot reports), that get circulated only after a plane has encountered turbulence significant enough to report. This results in wide diversions, often without a guarantee of complete avoidance.

This is an intractable problem that airlines are continually challenged by and have been looking for solutions, as far back as we can find.

Ultimately, what is limiting the effectiveness of airlines' efforts is the current level of technology involved with turbulence prediction. The granularity of current systems is 100x100km, and are primarily based on vertical wind shear. This creates a gap between what is detectable by current systems, and the prevalence of turbulence encountered by pilots.

Many academic studies have demonstrated that temperature fluctuations induced by climate change can cause increased wind shear, resulting in a greater incidence of turbulence in both frequency and severity. This phenomenon is projected to impose additional costs on airlines while they attempt to uphold the same level of safety as at present.

For example, Williams (2017) of the University of Reading posits that the occurrence of turbulence is anticipated to experience a significant upsurge concomitant with the rise in CO2 concentration.

> *"(...) when the atmospheric carbon dioxide concentration is doubled (280ppm to 580ppm). By converting the diagnostics into eddy dissipation rates, we find that the ensemble average airspace volume containing light clear-air turbulence increases by 59% (with an intra-ensemble range of 43% – 68%), light-to-moderate by 75% (39% – 96%), moderate by 94% (37% – 118%), moderate-to-severe by 127% (30% – 170%), and severe by 149% (36% – 188%). These results suggest that the prevalence of transatlantic wintertime clear-air turbulence will increase significantly in all aviation-relevant strength categories as the climate*

> *changes." ("Increased Light, Moderate, and Severe Clear-Air Turbulence in Response to Climate Change", P. Williams, Univ. of Reading)*

As turbulence intensifies in frequency and magnitude, the conventional method to steer clear of turbulence, again comprised of relying on vertical wind shear prediction, prior experience, and pilot reports (PIREPs), is expected to lose its effectiveness. Consequently, it is understood that the number of turbulence related incidents experienced by airlines will increase.

Date	Flight	Incident details	Casualties
March, 2023	LH469	Brief but severe turbulence happened about 90 minutes after take off and resulted in minor injuries to some passengers (CNN)	7 people transported to the hospital
March, 2023	DT652	When the flight was passing over the Democratic Republic of Congo, it experienced thorough severe turbulence (Simple Flying)	10 people were injured
March, 2023	WN3094	When the flight began to descend towards Raleigh, the plane experienced extreme turbulence (The Guardian)	2+ people became ill
December, 2022	HA035	Flight faced severe turbulence half an hour before landing. Many were seriously injured and were taken to the emergency room (Simple Flying)	35+ people were treated when plane landed, and several (20 according to rep) taken to the hospital
December, 2022	UA128	The flight experienced severe turbulence that was unexpected while en route to Houston (CNN)	5+ people transported to the hospital
October, 2022	AR1133	Over the Atlantic Ocean entering the American continent, the flight encountered severe turbulence (The Aviation Herald)	12 people were injured, 3 people transported to the hospital
August, 2022	DL394	During the cruise portion of the flight at flight level 340, the aircraft encountered turbulence (Simple Flying)	3 people were injured
July, 2022	AA3609	The flight experienced "unexpected turbulence" so that eventually caused the flight to divert to an Alabama airport, officials said (CNBC)	8 people transported to the hospital
May, 2022	SG91	The light turbulence began around 35 minutes before landing, worsening as the plane started descending. The DGCA said that the aircraft experienced vertical load factors between +2.64G and -1.36G during descent (Simple Flying)	17 people were injured

Table 1.

List of recent turbulence incidents

The list is not exhaustive

Source: NABLA Mobility analysis, Simple Flying, CNN, Newsweek

3. Solution

Pair a machine learning based turbulence prediction system with a multi-objective optimization to generate recommendations to inform and support pilot decision making. With this method, it is possible to map more sites of turbulence, accounting for more types of turbulence, with greater accuracy, and plot a safe, efficient path to the destination. Due to the dynamic nature of this problem machine learning models are the only way to untangle the intense complexity involved.

Consequently, we refer to our solution as Untangle.

TURBULENCE MODEL

As turbulence is a continual and constant concern for airlines. A new tool that is effective beyond the scope of traditional techniques is required to minimize the impacts of current turbulence levels, as well as expected future intensities. The only way to solve the problems described is to start with better information. This was accomplished through the adoption of a data-driven, machine learning approach, that additionally utilizes airlines' Quick Access Recorder(QAR) data for effective real-world validation.[1] Tailored specifically for aircraft operations, our turbulence prediction model stands as a pioneering system that has been implemented for practical use.

In actual flight operations, Vertical Wind Shear (VWS) is utilized to forecast turbulence. However, it is widely recognized that VWS alone cannot fully capture the complex dynamics of turbulence. To build a more comprehensive understanding into the model, additional factors such as horizontal wind shear, terrain, and others had to be taken into consideration. Terrain is specifically accounted for, due to it being a catalyst for a variety of turbulence types, by incorporating a physics-based framework. This extends the model beyond vertical wind shear to predict mountain induced waves and horizontal wind shear and other sources of instability. This is a significant step beyond the capability of current industry standard turbulence predictions.

Comparing our model to the existing VWS-based approach, we have achieved a prediction accuracy that is 7-14 times higher. Specifically, our model exhibits the ability to predict turbulence with an accuracy range of 45%-85% (This analysis was conducted on Moderate or greater turbulence at altitudes above 15,000 ft in the Japanese airspace from September 1, 2022, to November 30, 2022)

There is potential for future enhancements to the turbulence model that should be acknowledged, such as incorporating additional knowledge from pilots.

1. Quick Access Recorders (QAR) are flight data recorders that allow easy physical or remote access to the recordings of over 2000 flight parameters. The QAR is a secondary recorder utilized by the airline to review performance and safety, rather than the aircraft's primary Flight Data Recorder (FDR) which is required by aviation authorities for the purposes of investigating accidents.

Figure 2

The resolution comparison of turbulence prediction between the VWS model vs. NABLA Mobility model

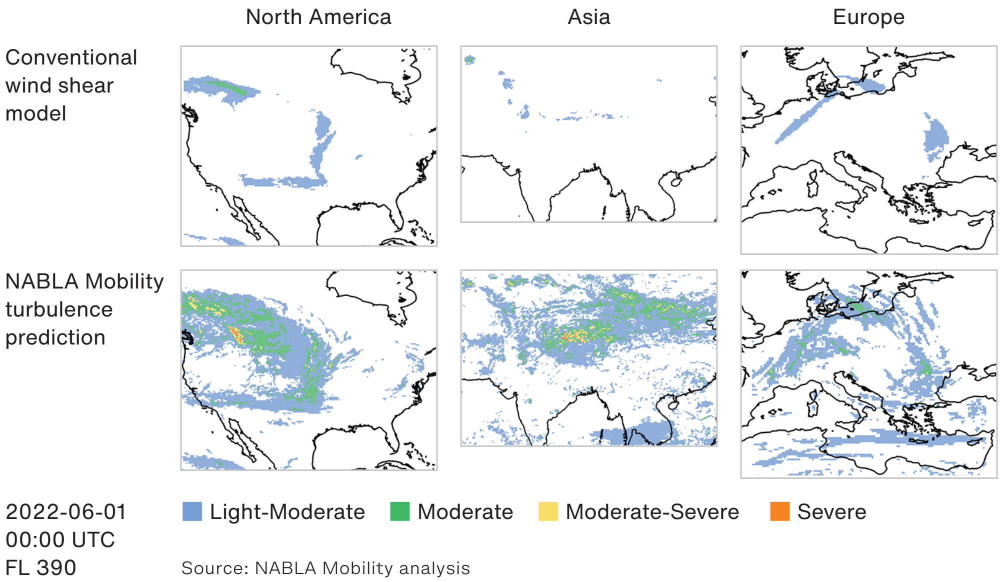
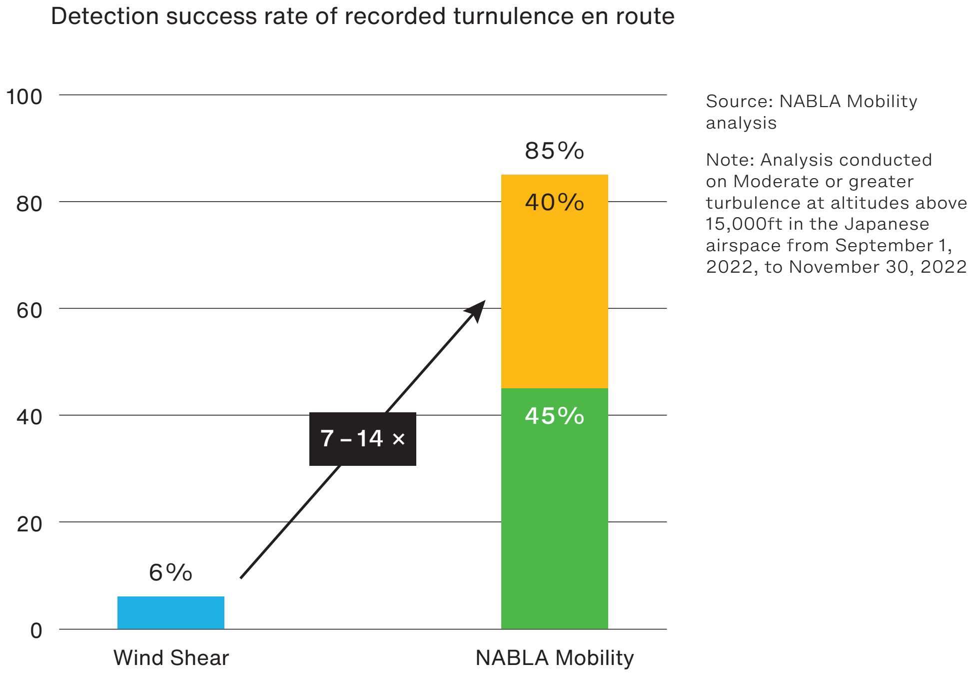


Figure 3

The accuracy of turbulence prediction between the VWS model vs. NABLA Mobility model



ADDITIONAL MODELS

To provide turbulence avoidance and altitude optimization solution as technological products used in real-world operations, we must also harness other machine-learning-based prediction models to ensure the feasibility and implementability of the Untangle solution.

Wind Prediction: The calculation of efficiency for each turbulence avoidance option relies heavily on highly accurate and fine-grained wind prediction data. However, it is acknowledged that the commonly used Global Spectral Model exhibits deviations of several tens of knots. By harnessing a machine learning model integrated with QAR data, we improve the accuracy and granularity of wind prediction, particularly within the aircraft's operating altitude and airspace.

Fuel Consumption Prediction: In order to precisely capture the opportunity to avoid turbulence, accurate fuel consumption prediction at the granularity of each tail number is essential. By combining physical and machine learning models, we have successfully attained highly precise fuel consumption predictions that account for the unique characteristics of each aircraft at the tail number level.

		NABLA Mobility	Company A	Company B	Company C	Company D	Company E
Product features		Decision making support tool balancing safety, cost, and decarbon-ization "Weave"	Cruise altitude optimization tool for pilots	Altitude and route optimization tool for pilots	Tool for proposing fuel-saving measures to pilots based on past analysis	Tool for proposing optimal climb setting and direct-to options to pilots	Flight plan optimization tool for dispatchers
Consideration of operational performance factors	Safety	✓ System calculation based on exact turbulence prediction	✗ Pilot judgement	△ System calculates based on past turbulence records	✗ System calculates based on flight log	✗ Pilot judgement	△ System uses restricted turbulence predictions for consideration
	Decarbon-ization	✓ Beta version launched	✓ Implemented	✓ Implemented	✓ Implemented	✓ Implemented	✓ Implemented
	Punctuality	✓ Punctuality calculated with altitude optimization and direct-to	✓ Punctuality calculated	✓ Punctuality calculated with altitude optimization	△ Punctuality calculated with reduced flight time by direct-to	△ Punctuality calculated with reduced flight time by direct-to	✓ Punctuality calculated with route optimization
Prediction of uncertainties	Turbulence	✓ Comprehensive turbulence prediction	✗ Limited to providing past records	✗ Limited to providing past records	✗ No prediction available	✗ No prediction available	△ Prediction generated by limited component
	Traffic	✓ Unique prediction technology for short-term future	✗ No prediction available	△ Actual traffic data from ADS-B, etc.	✗ No prediction available	✗ No prediction available	✓ Unique prediction technology for airspace traffic
	Weather	△ Enhanced high resolution data leveraging flight operation data	✗ Medium resolution data from UK Met	✗ Medium resolution data from weather vendors (i.e. IBM)	✗ Medium resolution data from weather vendors (i.e. IBM)	✗ Medium resolution data from weather vendors (i.e. IBM)	✗ Medium resolution data from weather vendors (i.e. IBM)

Table 2

Comparison of characteristics between market-available solutions

✓ Implementing the necessary technology and data

△ Partially implementing the necessary technology and data

✗ Do not possess the necessary technology and data

Note: Analysis contains information researched by NABLA Mobility independently through publicly available information and interviews with industry stakeholders thus this analysis may not cover non-public information

Source: NABLA Mobility analysis

Traffic Prediction: When Air Traffic Control (ATC) assesses and approves flight route requests from aircraft, they take into account the prevailing traffic conditions within the airspace. However, the existing traffic prediction solely relies on extrapolating the route based on the present direction and speed, lacking realistic situational awareness. By adopting automated driving traffic prediction algorithms, we have developed a traffic flow prediction model that incorporates aircraft interactions, enabling it to generate highly accurate predictions for up to 15 minutes ahead of time.

MULTI-OBJECTIVE OPTIMIZATIONS

Combining and prioritizing the output of these models allows us to balance the primary operational objectives that pilots must contend with daily: safety, efficiency, punctuality, passenger comfort. This is accomplished with a multi-objective altitude optimization model, that identifies optimal flight opportunities, minimizing potential encounters with turbulence.

The factors that determine an "optimal" method to avoid turbulence are influenced by the unique circumstances of each flight. These include the priority of operational objectives, wind profiles, airspace restrictions, and air traffic control (ATC) protocols (i.e. pilots may opt to navigate through turbulence in order to prioritize punctuality), and aircraft weight.

For every flight, the multi-objective optimization model calculates the optimal cruising altitude, and the optimal point to deviate from the original flight plan. Additionally, it calculates and accounts for changes to aircraft weight and weather caused by changes to the route made during optimization.

Additionally, airlines have the flexibility to define their own threshold of acceptable turbulence intensity. This allows each operations team to define the level of comfort and safety they prefer in order to meet their objectives. Based on this preference, the model calculates the most efficient and punctual options, striking an optimal balance between the two objectives.

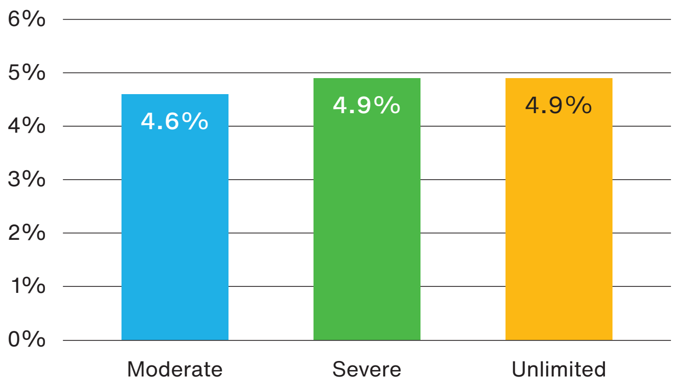
The optimizations are currently achieving these safety and efficiency metrics through altitude adjustments, however in the future there is the potential to extend the capabilities of the model to enable direct-to recommendations.

In contrast, existing solutions on the market fall short of capturing precise opportunities to avoid turbulence compared to our Untangle solution. This limitation can be attributed to reliance upon less accurate turbulence prediction data, and partial consideration of multiple key operational objectives.

Figure 4

Average cruise phase fuel reduction (by turbulence threshold, reduction % compared to flight plan; 4.6% = 4.6% reduced compared to the flight plan)

Average cruise phase fuel reduction per turbulence threshold
(Reduction % compared to flight plan; 4.6% = 4.6% reduced)



Source: NABLA Mobility analysis

Note: Analysis was conducted based on past QAR data (a random sample of 90+ flights' actual flight QAR data, July 2022 to November 2022; approximately 20 flights per month). Altitude coverage >15,000 ft, mainly for short-haul flights lasting less than 3.0 flight hours. The sample flights were limited to Japanese air space.

Even setting the turbulence threshold "to Moderate" achieves an average 4.6% fuel reduction

RECOMMENDATIONS

The result of the multiple methods of optimization is a set of optimized variants of the original flight plan. Each optimized variant is tailored to different operational objectives: safety optimized variant, fuel optimized variant, time optimized variant.

Each details the altitude changes made to the original flight plan, that are unique to the time and the weather conditions. These optimized variants are provided to pilots as recommendations, allowing them to supplement their expertise with increased situational awareness. Pilots can assess the flight with greater detail and choose an optimized variant based on the priority of the moment, and their experience.

VALIDATION

An analysis was conducted based on past QAR data that analyzed a random sample of 90+ flights' actual flight QAR data (July 2022 to November 2022; approximately 20 flights per month) covering altitudes greater than 15,000 ft and for short-haul flights lasting less than 3.0 flight hours. The samples were taken from flights within Japanese air space.

A natural tradeoff exists depending on where the turbulence avoidance threshold is set. Asking Untangle to optimize a route while the turbulence avoidance threshold is set to avoid lower intensities, such as avoiding all moderate turbulence, results in less fuel reduction, as more fuel is required to go around. However it turned out to be less than expected during the analysis. Even when the threshold is set to avoid moderate turbulence, a fuel reduction of approximately 4.6% is achievable.

4. Product

In order to facilitate real-world outcomes, two access methods have been developed for easy integration to existing operations workflows.

As a technology focused startup, rather than simply focusing on research, the purpose of this development is to deliver substantive positive impact and drive real-world outcomes. To that end, Untangle has been made accessible both as an API and through a standalone software application.

Providing API access facilitates easy integration into existing commercial aviation software. This method allows airlines to make use of the Untangle's capabilities without having to make changes to their workflow, move away from existing software, or overhaul integrations.

Additionally, we developed and launched a standalone application, called Weave. This delivers the same turbulence avoidance and altitude optimization solution as delivered through API access, while additionally briefing the pilot on updates and changes to the route based on the Untangle's output. This affords options to airlines of differing sizes and workflows. The application also serves as a demonstration platform.

Both methods are delivered as services (SaaS), while requiring minimal integration. This method allows us to deliver the maximum amount of benefit to pilots and operations teams with the least investment. Similarly, our core ML and AI technologies were built and operate in a modular fashion, meaning that, not only will we be able to deliver improvement updates without reintegration, but as new modules are developed, additional technologies can be delivered to pilots and operations teams in a seamless manner.

Lastly, because this method deals with the fundamental physics of flying through the atmosphere, this solution is equally applicable to all aircraft, regardless of engine type, fuel type, or airframe type. Also, it can be applied to existing fleets without modifications, and works equally well when fleets are refreshed or modified.

Safety enhancements

TURBULENCE AVOIDANCE

Avoiding MODERATE and above
Types of turbulence avoided: CAT, MWT

TURBULENCE PREDICTION

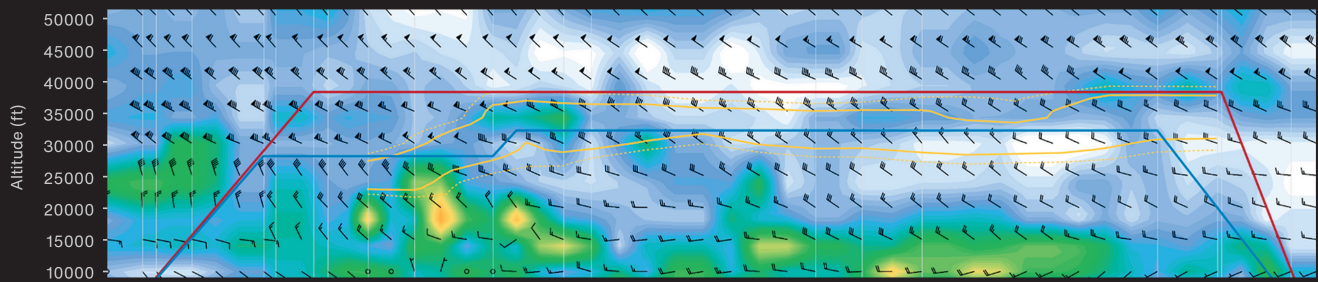
Based on these safety enhancements, the maximum turbulence intensity to be encountered: Light-to-Moderate

Benefits

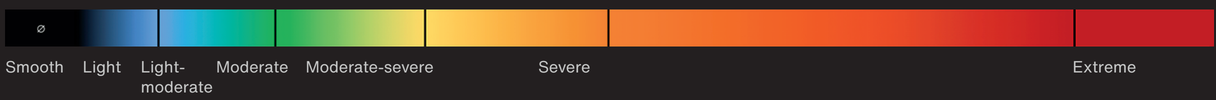
OPTIMIZATIONS BASED ON SAFETY ENHANCEMENTS

Fuel optimization: –97 lbs
Time optimization: –2 mins

Solution details



TURBULENCE



TOC — TOC: level off at FL280

Altitude optimization — DONKY begin climb to FL320

TOD — TOD: descend from FL320

Figure 5

Sample taken from stand alone application 'Weave' showing both original and optimized routes for comparison.

5. Conclusion

The traditional trade-off between safety and fuel efficiency no longer needs to define the flight operations paradigm. With a granular understanding of conditions, and an altitude optimizer that finds the most efficient path around adverse conditions, both safety and efficiency can be achieved.

Not only does turbulence pose an intractable problem that aviation has been trying to solve due to the significant detrimental costs, but the risks associated with turbulence for airline operations are expected to intensify due to continuing climate change. As the frequency, severity, and patterns of turbulence change, airlines face increasing challenges in avoiding turbulence with traditional operations. Ensuring safety in an increasingly adverse context is only possible by introducing technologies that represent a new level of capability, and change the constraints of the problem at hand.

Our solution for turbulence avoidance and altitude optimization offers a remedy to mitigate those costs. By harnessing the power of machine learning-based predictions and optimizations, we can predict the turbulence for 45% – 85%, meaning a 7x to 14x higher rate than the commonly used VWS-based model. By pairing this resolution increase with altitude optimization technology to precisely avoid turbulence, airlines can reduce consumption by up to an extra 5% during cruise phase, in addition to optimized flight planning.

By adopting the solution, airlines are not only able to avoid turbulence effectively but also achieve better operational resilience. We are dedicated to assisting airlines and we would be thrilled to conduct a detailed analysis to assess how our solution benefits you in your specific operational context.

To find out more, arrange an in-depth conversation or demo, please reach out to the contact below.

WHO WE ARE

1. **NABLA Mobility**
2. CEO:
   Shinji TANAKA,
   Founder & CEO
3. Location:
   Tokyo, Japan
4. Investors:
   a. the Boeing Company
   b. Incubate Fund
   c. DNX ventures
   d. ITOCHU Technology Ventures
   e. Mitsubishi UFJ Capital
5. Partnerships & Collaborations:
   a. Peach Aviation
   b. University of Tokyo, Department of Aeronautics and Astronautics.
   c. Aviation Technology Directorate of Japan Aerospace Exploration Agency (JAXA)
   d. Development Bank of Japan
6. Contact:
   a. **Sangyoung LEE**, General Manager of Business Development
   b. corporate@nabla-mobility.com

NABLA Mobility

NABLA Mobility Inc.

inquiries@nabla-mobility.com

www.nabla-mobility.com

COVER PHOTO
Damon Lam