Prediction of Terminal-Area Weather Penetration on the Basis of Operational Factors

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Convective weather is known to reduce airspace capacity, but the extent of the impact is not well understood. Understanding how weather affects terminal area capacity is essential for quantification of the uncertainty in weather forecasts and, in particular, the degree of accuracy of the forecast. With this foundation, the question emerges as to the feasibility and possible effectiveness of an optimal mitigation strategy. Research has focused on the overlap between convective weather cells and air routes but has not sufficiently analyzed the differences that arise from factors such as aircraft types and pilot behavior. This paper examines the interactions between convective weather and aircraft trajectories in the arrival airspace surrounding Chicago O’Hare International Airport in Illinois. Case studies based on operational data are used to determine potentially relevant operational factors, and a predictive model is built with these factors to forecast whether a flight will pass through hazardous weather. The results of the analysis suggest that these operational factors are secondary to the weather itself in determining whether a pilot will deviate from or penetrate hazardous weather.

The increasing demand for air travel in the United States has strained the capacity of the National Airspace System. Any further reduction in capacity because of poor weather or other disruptions can result in significant delays. This situation is especially true for summer convective weather systems, which can grow and decay rapidly and are difficult to forecast. The impact of these storms is compounded by the fact that they occur in summer, when demand for air travel is at its highest.

Although convective weather is known to affect air traffic operations and reduce airspace capacity, the extent to which capacity is reduced as a result of weather is not well understood. Prior research has mostly focused on (a) the types of weather that disrupt traffic, (b) rerouting around weather, and (c) the effect of convective weather on controller workload, without considering flight-specific factors. An examination of weather and trajectory data shows that, while pilots typically avoid hazardous weather, some of them penetrate severe weather cells, both en route and within the terminal area. This paper explores operational factors that may drive pilot behavior associated with deviation from, or penetration of, weather. The analysis focuses primarily on weather penetration behavior within the terminal area surrounding airports.

BACKGROUND

Summer convective storms, commonly known as thunderstorms, occur in many parts of the continental United States and typically form in the afternoon. Convective storms are associated with heavy rain and severe turbulence. Because they grow and decay relatively quickly, they can be difficult to forecast.

The convective weather avoidance model (CWAM) was developed at the Lincoln Laboratory of the Massachusetts Institute of Technology (1–3). This model forecasts weather avoidance fields that predict the probability of pilot deviation based solely on weather-related features such as the height and intensity of a storm. For weather inputs, the model considers the vertically integrated liquid (VIL) and the height of the echo top. VIL represents the total amount of liquid in a vertical column of the atmosphere and is divided into six levels chosen to correspond to pilots’ perceived threat levels in previously used weather displays (4). Level 3 VIL corresponds to a yellow threat level and Level 6 to a red threat level. The height of the echo top is the altitude of the highest clouds containing weather.

Several versions of CWAM, for various types of airspace, have been developed and refined. For en route traffic, the most important indicator of pilot deviation was found to be the difference between flight altitude and echo top height followed by Level 3 VIL coverage within 16 km. Recent results for arrival flows have found that, because pilots are not typically able to fly over storms, the absolute echo top height was a good indicator of weather avoidance in the terminal area, in addition to weather coverage within 4 km (5). The terminal area version of CWAM is used in the studies presented in this paper.

Weather Avoidance Field

To understand how the weather avoidance field (WAF) identifies areas of weather that pilots are likely to avoid, a look at an example is instructive. Figure 1 shows VIL, echo tops, and resultant WAF in the terminal area for Chicago O’Hare International Airport (ORD) in Illinois on June 12, 2008, at 20:17:30Z (with Z representing Coordinated Universal Time). The arrival trajectories are color coded in accordance with the maximum WAF penetrated in the terminal area; all departures are grey. The WAF eliminates much
of the light rain that has little or no effect on aviation. Furthermore, not all VIL pixels of Level 3 or above translate to high WAF; some smaller cells have low echo tops, which CWAM has found likely to be penetrated by pilots; these are accordingly assigned a lower WAF.

The WAF encapsulates a pilot’s willingness to penetrate severe weather solely on the basis of weather features. However, operational factors are believed to influence pilot decision making. This paper explores whether these operational factors are in fact significant and attempts to predict—based on operational features—when pilots will be willing to penetrate regions of high WAF.

Comparison with Actual Weather

Because some pixels with low-level VILs possess high WAFs simply from their proximity to higher VIL levels, aircraft passing through high WAFs may not be penetrating weather. Another possibility is that they are flying over weather. Therefore, checking whether flights are flying through severe weather when they penetrate high WAFs may provide useful information. To this end, the distribution of the actual VIL penetrated by each flight, sorted by WAF value, is plotted in Figure 2. For example, for all pilots who flew through a given WAF, the figure shows the VIL levels that they actually penetrated. The left bar in
each pair indicates the VIL distribution; the right bar removes those instances in which a flight was at or above the echo top height.

Figure 2 validates the use of the WAF. First, overflying is rare and does not skew the results. In more than 95% of cases, aircraft do not overfly weather in the terminal area, likely because they are in descent. Second, a strong correlation exists between high WAFs and high VIL levels. Aircraft that penetrated WAFs of 80 or more had a greater than 80% chance of penetrating Level 3+ VILs. Flights that flew through WAFs of 80 or more but penetrated only Level 1 or 2 WAFs flew within 4 km of Level 3+ VILs.

Terminal Area Operations

This paper focuses on arrival operations in the terminal area and uses the ORD as an example. Although terminal radar approach control facilities are typically irregularly shaped, a circular region simplifies analysis. Characteristics that define the terminal area and may influence pilot behavior are considered in determining the radius. Aircraft trajectories are more constrained, both vertically and horizontally, in the terminal area. Aircraft frequently fly over convective weather in en route airspace; an aircraft that has already begun its descent may not be able to do so. Furthermore, arrival routes are quite structured, especially at congested airports such as ORD, and air traffic controllers may be reluctant to allow aircraft to deviate. While it is difficult to quantify the degree to which pilots have flexibility to deviate from established flight paths, one can determine when arrivals typically begin their descents. Aircraft landing at ORD typically begin their descent sequence about 200 km from the airport. Excluding routes of less than 300 km, most flights begin their descent sequences between 200 and 250 km from the airport. From the preceding observations, the terminal area is defined as a circle of radius 200 km around the airport.

Figure 2 VIL distribution for each WAF value (right bar in each pair removes flights that were at or above echo top height).

METHODOLOGY

The methodology adopted in this paper combines case study analysis with predictive modeling. Case studies are used to identify potentially relevant features, and a predictive model is built to evaluate their relevance. The following section discusses the case studies undertaken, focusing on instances in which aircraft penetrated severe weather. Along with observations from air traffic controllers and other researchers studying pilot behavior related to weather, these case studies inform the identification of features used in the predictive model.

CASE STUDIES

Case studies and discussions with people in the field have been extremely helpful in guiding the development of this research, for both (a) understanding the evolution of weather throughout the day and how this weather evolution affects the terminal and (b) identifying features that affect pilot behavior. This section is divided into two parts. First, it describes one of the eight case days in the study so that the reader can envision how weather evolves throughout a day and the impact this evolution has on traffic. Second, it lists some of the recurring themes frequently observed in the case studies and mentioned by people familiar with the field as possible reasons for severe weather penetration.

Overview of Case Day, July 2, 2008

This section describes one of the eight case days in the data set, July 2, 2008. Similar analyses were performed for each of the other case days, with comparable results. As is fairly common during the summer, convective weather affected the ORD terminal area from about 1500Z (10:00 a.m. local time) until about 0300Z the
next day (10:00 p.m. local time). Figure 3 gives a brief overview of the case day. The bars indicate the number of flights landing at the airport at any given time. They are color coded in relation to the maximum WAF penetrated by the aircraft within the terminal area. Grey indicates that the aircraft did not fly through any inclement weather. The red line indicates the percentage of the terminal area containing WAFs of 80 or greater; this value roughly represents the severe weather coverage in the terminal area. Figure 4 shows a series of snapshots in time, which indicate the evolution of WAFs throughout the day.

Generally, as the amount of weather in the terminal area increases, the number of flights decreases. During the peak of the weather impact, from about 2200Z to 0000Z, traffic drops quite severely. Furthermore, most of these flights penetrate severe weather. While the drop in traffic can be attributed to the ground delay and ground stop programs in place for ORD, the relatively large fraction of flights that penetrates weather during the convective weather event suggests that the airspace was likely close to capacity.

Flights are not universally more likely to penetrate severe weather when greater severe weather coverage occurs in the terminal area, although these quantities are correlated. Few flights penetrate weather—and even then only the lower WAF levels—in the early part of the day, while the weather is still growing in coverage and intensity. During the latter part of the day, as the weather is decaying and moving from the terminal area, more flights penetrate high WAFs, even WAFs of 80 and above, despite fewer flights in the air. Whether these penetration patterns are the result of the nature of the weather (decaying weather may pose less of a threat) or of operational reasons is unclear.

A detailed case study will shed light on how weather and terminal area procedures interact to determine aircraft penetration of, or deviation from, severe weather. In each subplot in Figure 4, a black circle indicates the terminal area, with a radius of 200 km around ORD. The solid lines are the trajectories up to that time, and the dotted lines are future trajectory points. A triangle indicates the current position of each aircraft. Gray trajectories are departures. As in Figure 3, arrivals are color coded in relation to the highest WAF that the aircraft penetrates within the terminal area. The color bar to the right represents background WAF.

**Detailed Chronology**

On July 2, 2008, ORD was affected by several small lines of convective weather cells that severely disrupted operations. Weather first entered the terminal area around 1400Z; however, most of this first line stayed north of the airport, with minimal effects on traffic: only three arriving flights penetrated WAFs of more than 80. Because of its position, the weather did not affect most standard arrival routes.

Air traffic flow managers noted the impending arrival of a second series of convective cells that was expected to pass almost directly above the airport. These cells were less severe than the first line but caused a far greater disruption because of their location. At 1534Z, well before the arrival of the second series of cells, a ground delay program (GDP) was initiated. The GDP, which affected all flights departing from the continental United States and Canada, was scheduled to take effect at 1800Z, when the second series of cells was expected to enter the terminal area.

The second series of storms entered the terminal area around 1915Z, traveling due east. These storms had cells of Levels 5 and 6 VIL and correspondingly had WAFs of 100. They also grew in size as they moved eastward toward the airport. Figure 4 shows that the departure streams shifted south in response to this weather. Furthermore, because of the GDP, the number of flights attempting to land at ORD had begun to decrease.

At the same time, the first line of weather to the north began to affect the northeast arrival streams. These streams first shifted south in an attempt to fly around the weather and were eventually rerouted behind the storm through lower WAFs. They were probably vectored through the storm by air traffic controllers in a continuous flow. As the weather intensified, fewer and fewer pilots approached from the northeast, and the corner post was shut down.
FIGURE 4  ORD terminal area on July 2 and 3, 2008, showing evolution of WAFs at (a) 1500Z, (b) 1700Z, (c) 1900Z, (d) 2100Z, (e) 2200Z, (f) 2300Z, (g) 0100Z, and (h) 0300Z.
The second line of cells from the west continued to progress toward the airport, reaching ORD shortly after 2100Z. The extent of this line was smaller than that of the first but of similar intensity. As this storm front approached the airport, more than 20 aircraft penetrated severe weather within the terminal area. The situation quickly became untenable, and a ground stop was initiated at 2103Z and extended at 2121Z. It was downgraded to a GDP at 2151Z.

This ground stop was triggered, at least in part, by the large number of aircraft penetrating severe weather. In most cases, as Figure 4 shows, flights simply had no other choice if they wanted to land at ORD, particularly once the storm was directly over the airport (for example, around 2200Z). In some cases, pilots attempted to deviate around a large cell but instead penetrated the cell at some point. This behavior is partly attributable to the nature of approach paths: aircraft arriving from the west had to fly around the weather to use the active runway.

After 2200Z, the weather cells began to decay and move from the terminal area. Nevertheless, several flights flew through the severe weather. While some streams were still visible, the overall patterns were sufficiently unstructured that pilots likely chose their own paths through the weather. For example, at 0100Z, an aircraft briefly flew through a WAF of 100, although most others in the same stream did not. Observations such as these suggest variability in the risk tolerances of pilots flying through weather.

Even when the weather is decaying, its location relative to the airport is important. At 0100Z, when the weather was farther from the airport, relatively few pilots penetrated severe weather. Most of those who did intersected the boundaries of the weather cells and did not fly directly through the cells. Yet, when the same weather reached the airport around 0300Z, pilots who wished to land had no choice but to penetrate the severe weather. This observation partially explains why a greater number of severe-weather penetrations occurred when the weather was decaying than earlier in the storm.

By 0240Z, the weather in the terminal area had sufficiently decayed for GDP to be cancelled. The decreased levels of traffic meant that individual flights had greater flexibility to deviate around the weather. Given these factors, a surprising number of flights flew through WAFs between 40 and 100. Such periods prove useful for investigating whether operational factors influence the reasons that certain flights penetrated severe weather while others avoided it.

**Conclusions from Case Study**

Many factors influence whether a pilot in the terminal area will choose to deviate around weather; indeed, many factors influence whether a pilot will even be in the terminal area at the time of a weather event. First, initiatives for traffic flow management will reduce the number of flights into an airport during the worst weather (6). The reduced traffic may give the remaining flights greater flexibility to deviate. The specifics of initiatives for traffic flow management can also provide insight into the capacity of the airspace. For example, the initiation of a ground stop at 2103Z indicates that air traffic controllers felt the need to reduce the number of flights in the terminal area. Second, the proximity of severe weather to the airport is an important factor in determining whether pilots choose to deviate. When the severe weather is unavoidable, many pilots appear to be willing to penetrate it. Third, at least one period in which pilots made a variety of choices on whether to penetrate severe weather was identified on this case study day. Situations such as these may help identify operational factors that influence aircraft penetration of severe weather and the associated decisions by pilots.

While the preceding discussion focused on a particular case study day, similar assessments were conducted for eight days in 2008, all of which included significant convective activity in the Chicago area.

**Factors Potentially Influencing Severe Weather Penetration**

The preceding section described evolution of weather through a case study day and the response of air traffic managers to changing weather conditions. This section lists additional factors that may contribute to pilot willingness to penetrate severe weather. These observations combined guide the feature extraction process.

**Proximity to Weather Cells**

Aircraft frequently fly close to severe weather, in some cases within a few kilometers of very heavy storms. As a consequence, aircraft may occasionally penetrate a severe weather cell for brief periods. Furthermore, because the kernel for the WAF is 4 km, occasionally an aircraft may appear to be flying through severe weather when it is only flying quite close to it.

**Aircraft Size**

Several domain experts hypothesized that large aircraft might be more likely to penetrate severe weather. In addition to being less able to withstand severe weather conditions, small aircraft on shorter routes may be more frequently subject to ground delays during weather events.

**Apparent Gaps in Storm Fronts**

Aircraft were frequently seen flying through lines of severe storms and deviating as needed to avoid the worst weather. Even lines of severe thunderstorms have small gaps in the weather that pilots or air traffic controllers are able to observe and exploit to reduce its impact.

Although identifying these gaps from the data is difficult, indicators associated with such behavior may be detectable. Pilots observing and exploiting these small gaps may fly longer routes than usual. These aircraft may also be more likely not to belong to a traffic stream, as they would individually find their way through gaps in the weather.

**Perturbation of Traffic Flows at Onset of Severe Weather**

As severe weather moves across the terminal area, aircraft flows commonly deflect slightly to avoid passing through it. Eventually, aircraft fly behind the storm, as seen in Figure 4 around 1900Z and again around 0100Z.
Flight Delays

Another potential factor influencing a pilot’s decision to deviate from weather is the delay status of the flight. A pilot who has already been significantly delayed may risk penetrating weather rather than delay the flight further by flying around the weather.

PREDICTIVE MODEL OF SEVERE WEATHER PENETRATION

The case studies described in the preceding section identified several factors that may increase the likelihood of penetration of severe weather. A predictive model using random forests was developed to determine which of these factors had statistically significant skill and to quantify their predictive power.

Many of the input traffic data for the predictive model were taken from the Enhanced Traffic Management System (ETMS) (7) and Aviation System Performance Metrics (ASPM) (8) databases. Trajectories in the ETMS database were matched to their corresponding flights in the ASPM database with a 97% success rate. The unmatched flights were not included in the modeling. While some potential features, such as aircraft type and delay status, can be directly extracted from the ETMS or ASPM database, other traffic-based indicators are more difficult to extract. The next section describes how some of these more complex features were determined. Once the features were extracted for each trajectory, a random forest prediction model was used to evaluate their relative skills.

Corner Posts and Traffic Flows

Aircraft flows at many major airports are routed into the terminal area through sets of gates known as corner posts. The first step in identifying traffic streams is to determine active corner posts and the proximity of flows around each of them. Each corner post is approximately 50 km from the airport; for consistency, this distance is used for all corner posts. The position of each flight in a certain period at a distance of 50 km from the airport is considered. Using these points, a k-medians clustering algorithm is used to determine the locations of the active corner posts (9). Typically, ORD has four cornerposts, although some of them may be closed because of weather. Their locations are generally stable to within a few degrees. The k-medians clustering algorithm is run with $k = 1, 2, \ldots, 8$, and the value with the lowest error is used to identify corner posts.

Normally, flights arriving from different directions will be merged into a single stream before they reach a corner post. During fair weather, these streams are quite precise; once merged into the stream, each pilot follows almost exactly the same trajectory. However, during convective weather events, pilots may deviate significantly from the path defined by the preceding aircraft, despite being assigned to the same corner post. Therefore, the deviation distance between subsequent pilots on each corner post is also measured. Groups of pilots that follow nearly identical paths are considered substreams.

Once a substream has been identified, several additional features can be extracted. For example, one can compare an aircraft’s weather penetration behavior with that of the one immediately preceding it or consider whether an aircraft is the first or last in that particular substream. A pilot penetrating severe weather may notify the air traffic controller of turbulence, which might cause subsequent aircraft to be routed differently to avoid the weather. If this occurrence is common, severe weather penetrations may be associated with being the last pilot in a given substream.

Random Forest Model

Once the potential features were extracted, a random forest model was constructed to evaluate the impact of these operational factors on weather penetration. The model was a binary predictor of whether a particular flight would penetrate severe weather (i.e., a WAF threshold of 80% or more) within the terminal area.

Random forests are a natural extension of decision trees and were first described by Breiman in 2001 (10) and others in 2009 (11). Random forest models were chosen here because they are quite robust and can handle many correlated variables. The diversity of random forests also avoids the problem of overfitting that is sometimes encountered with decision trees.

A random forest works by creating many decision trees through use of random subsets of the features and the data in each one. The model developed in this research used 500 trees in each forest, with each tree drawing four predictors at random. The trees were trained on oversampled subsets of flights, each with equal numbers of flights that did and did not penetrate severe weather. Each tree then voted on the outcome of the prediction variable: The sensitivity of the model could be altered by adjusting the threshold for a yes vote.

The model was trained and tested by using eight random partitions of the data set. A summary of results is shown in Table 1 for several vote thresholds. The random forest model appears to perform reasonably well on the test data set, achieving accuracy rates of up to 90%. The overall accuracy was, however, skewed toward the negative prediction. The lack of oversampling in the test data explains the high false-alarm rate.

Sensitivity Analysis

The sensitivity of the model depends on the vote threshold, which controls the balance between false alarms and missed detections. The false-alarm rate increases rapidly as the vote threshold is lowered. At the same time, decreasing the vote threshold lowers the number of missed detections. A reasonable balance point seems to be somewhere between 0.3 and 0.5 and depends on the relative costs of missed detections and false alarms. The trade-off is plotted in Figure 5.

| Threshold for Yes Vote | Predicted | Actual Yes | Actual No |
|------------------------|-----------|------------|-----------|
| 0.7                    | Yes       | 34 (3)     | 145 (28)  |
|                        | No        | 33 (6)     | 4,235 (59)|
| 0.5                    | Yes       | 51 (4)     | 556 (56)  |
|                        | No        | 15 (4)     | 3,825 (70)|
| 0.3                    | Yes       | 63 (5)     | 1,728 (186)|
|                        | No        | 4 (4)      | 2,651 (206)|
| 0.1                    | Yes       | 66 (7)     | 3,662 (300)|
|                        | No        | 0 (0)      | 717 (293) |
Variable Importance

The random forest model ranks features by skill. To do this, it randomly permutes the values of each variable and measures the decrease in accuracy of the resulting tree by means of a Gini index \((10)\). This process is repeated for all trees in the forest that contain the variable in question. The resulting average is the variable importance; a higher value indicates greater skill. These importance values were computed for an arbitrary run of the random forest model with vote threshold 0.5 and are summarized in Table 2.

The model indicates that the most importance features remain weather features; these have greater significance than all but one operational feature. The time spent in the terminal area is a significant feature, with longer terminal times correlated to higher likelihood of weather penetration. However, this feature can be known only after the flight has landed. A flight of longer range is also associated with higher likelihood of penetrating severe weather. Several possible reasons exist for this phenomenon. First, longer distances are correlated with larger aircraft, which may be better able to penetrate severe weather. Second, flights arriving from greater distances are less likely to be affected by GDPs or ground stops; as a result, severe weather periods may have a larger proportion of long-haul flights. Comparable in skill to the flight range is the number of preceding aircraft on the same approach path, with higher numbers corresponding to increased likelihood of severe weather penetration. This observation supports the hypothesis that pilots tend to follow established paths, perhaps through worsening weather. Despite these weak correlations, operational factors are not so significant as weather features in determining whether an aircraft will penetrate severe weather.

| Variable                                | Feature Importance |
|-----------------------------------------|--------------------|
| Weather coverage within 50 km of airport| 22.7               |
| Time spent in terminal area             | 16.3               |
| Weather coverage between 50 and 200 km from airport | 12.3           |
| Weather coverage within 200 km of airport | 11.6         |
| Flight range                            | 10.6               |
| Number of aircraft on same stream in past 30 min | 10.6           |
| Number of aircraft in terminal area     | 7.6                |
| Airline                                 | 6.9                |
| Number of aircraft on same stream in next 30 min | 6.7         |
| Airborne delay                          | 5.5                |
| Wheels-off delay                        | 5.4                |
| Pushback delay                          | 3.9                |
| Runway                                  | 3.2                |
| Corner post                             | 2.8                |
| Aircraft type                           | 0.3                |

CONCLUSIONS

This paper explored the relevance of operational features in predicting instances of an aircraft flying through severe weather. Several potential features were evaluated and found to have statistical significance: the two most significant nonweather features were flight range and total time spent in the terminal area. Several flow-based features were also found to have weak skill in predicting pilot behavior.

The random forest predictive model indicates that these operational features are a secondary effect and that the most important determinant of pilot behavior is the intensity and location of the weather itself. The results support the operational practice of treating all flights as equal when developing tactical weather mitigation strategies because they can be expected to behave in relatively similar ways in relation to weather penetration behavior. They also validate the use of WAFs in the terminal area. Finally, this study provides insights into the secondary operational factors that explain the variability in pilot behavior during severe convective weather events.
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