Relationship between Weather, Traffic and Delay Based on Empirical Methods

Banavar Sridhar and Sean S.M. Swei
NASA Ames Research Center, Moffett Field, CA 94035-1000

Introduction

The steady rise in demand for air transportation over the years has put much emphasis on the need for sophisticated air traffic flow management (TFM) within the National Airspace System (NAS). The NAS refers to hardware, software and people, including runways, radars, networks, FAA, airlines, etc., involved in air traffic management (ATM) in the US. One of the metrics that has been used to assess the performance of NAS is the actual delays provided through FAA's Air Traffic Operations Network (OPSNET). The OPSNET delay data includes those reportable delays, i.e. delays of 15 minutes or more experienced by Instrument Flight Rule (IFR) flights, submitted by the FAA facilities. These OPSNET delays are caused by the application of TFM initiatives in response to, for instance, weather conditions, increased traffic volume, equipment outages, airline operations, and runway conditions. TFM initiatives such as, ground stops, ground delay programs, rerouting, airborne holding, and miles-in-trail restrictions, are actions which are needed to control the air traffic demand to mitigate the demand-capacity imbalance due to the reduction in capacity. Consequently, TFM initiatives result in NAS delays. Of all the causes, weather has been identified as the most important causal factor for NAS delays. Therefore, in order to accurately assess the NAS performance, it has become necessary to create a baseline for NAS performance and establish a model which characterizes the relation between weather and NAS delays.

Previous Research

Several efforts have been made during the past few years to understand the connection between weather and delays both at the local and national levels. In Ref. 1, NAS performance was analyzed for the summer convective weather season using two delay metrics; namely, number of arrival and departure flights that are more than one hour late compared to their schedule, and total minutes of arrival delay. The weather score was computed at each hour's maximum storm intensity (on a scale from 1 to 6) multiplied by the number of flights scheduled to arrive that hour. Then, linear regression models were proposed to relate the delays to the weather score for a given day at a particular airport. Furthermore, a measure for system-wide (NAS) delays was provided by summing all the delays collected from each airport.

In Ref. 2, a method of evaluating NAS performance by normalizing for the effects of weather using an index, defined as the Weather Impacted Traffic Index (WITI), was described. WITI is an indicator of the number of aircraft affected by weather. This approach involves 1) assigning 1 to every grid cell $W_{i,j}$ of the weather grid W where severe weather is indicated and 0 elsewhere, 2) counting the number of aircraft in every grid cell $T_{i,j}$ of the weather grid W, and 3) computing the WITI at an instant of time k (typically at one minute intervals) from 1) and 2) as follows:

$$WITI(k) = \sum_{i=1}^{n}\sum_{j=1}^{m} T_{i,j}(k)\, W_{i,j}(k), \tag{1}$$

where n is the number of rows and m is the number of columns in the weather grid. Subsequently, a NAS average arrival delay model was developed by fitting the average WITI values and surface weather parameters at 49 major U.S. airports to the average arrival delays using linear regression. The central motivation of WITI computation is estimation of NAS performance based on some knowledge of traffic demand and weather patterns. Building upon this notion, the concept of using WITI as a measure of NAS delays (sum of departure, enroute, and arrival delays) was introduced in Ref. 3, in which the WITI was computed by including the number of aircraft in the extended regions of 20 miles around severe weather cells. The importance of using reference days for traffic demand was discussed in Ref. 3, and the reference days were identified as days that did not have significant weather, had significant traffic demand, and had low NAS delays. Using reference days as expected traffic demand, weather impacted WITI values were then computed in Eq. (1) for 65 days of weather data. Moreover, a set of statistical features based on WITI time histories and surface weather parameters was derived. These features, which included histogram based features and time-domain features, were functions of some of the most relevant determinants to the NAS delays. An empirical delay model was then developed for estimating NAS delays at the national level using WITI and surface weather features, and observed NAS delays. Mathematically, this problem was formulated as follows: If r is the number of features used and p is the number of days, then the estimation of NAS delays is to find a (unique) vector of coefficients $\hat{w}$ so that it solves the following minimization problem:

$$\min_{w}\left\{ \left\| Fw - D \right\| : \text{for all } w \in R^{r} \right\} \tag{2}$$

where $F \in R^{pxr}$ is the WITI and surface weather features, and $D \in R^{p}$ is the observed NAS delays. Therefore, the estimated NAS delays, denoted as $\hat{D}$, can be obtained as

$$\hat{D} = F\hat{w} \tag{3}$$

where $\hat{w}$ is the solution to Eq. (2).

Preliminary Results & Future Analyses

The objective of this paper is to extend the research in Ref. 3 in several different areas with a goal to establish an empirical relation between weather, traffic and NAS delays, so that it may be used as a means to measure the operational performance of NAS.

Selection of reference days

In this paper, the sensitivity analysis with respect to the variation of reference traffic days is performed for the 65 days of data previously collected and used in Ref. 3. The purpose of this analysis is to show the selection of specific reference days is somewhat insensitive to the actual computation of WITI counts. In other words, since weather has such a dominating effect, so long as a particular day of traffic has high demand and low OPSNET delays, it can be chosen as a reference day. To demonstrate the insensitivity, two different sets of reference days are used in computing WITI counts. Their comparisons in time domain and histogram (frequency based) are shown in Figures 1 and 2. These figures show no significant differences between the two choices of reference days. Therefore, either one can be used in the subsequent analysis.

Model improvement

The effect of weather is to reduce the capacity of the NAS by reducing the available resources at the airport and in the airspace. We view the NAS as a queuing network, and as the demand for resources as a fraction of the NAS capacity (denoted as ρ), increases, the NAS delay (denoted as D) exhibits the following relation

$$D \propto \frac{\rho}{1-\rho}, \tag{4}$$

where $0< \rho <1$. It can be deduced from Eq. (4) that for small ρ, D is proportional to ρ, and for moderate ρ, D is proportional to $\rho - \rho^2$. As $\rho \to 1$, the delay D increases in an exponential way. We use these observations to propose a piece-wise linear model for the delay characteristics.

In this paper, a piece-wise linear approach is proposed, in that the range of observed NAS delays is divided into three regions based on the locations of chosen two knots, and at each region estimated NAS delays is computed using the WITI features developed in Ref. 3, and following Eqs. (2) and (3). The optimal selection of the two knots using numerical search will be presented. NOWRAD weather data and OPSNET delay data covering a period of 108 days from April to July of 2005 will be used to evaluate the method (for extended regions around severe weather cells). Out of the108 days of data, the NAS delay estimation model will be developed using 90 days of data, and validated subsequently using the remaining 18 days of data.

Addition of flight cancellations

On days with significant weather, the airlines cancel flights as part of their effort to deal with weather. However, a cancelled flight does not contribute directly to the delay statistics. To further investigate weather induced NAS delay, the number of flight cancellations due to weather for the period of 108 days will also be collected and included in the NAS delay estimation process. The effect of adding these cancellation data to the delay estimation will be analyzed.

Towards envelopes

Figure 3 shows a scatter plot of the average WITI values over 24 hours period for the collected 108 days, and Figure 4 shows the plot of average WITI versus actual OPSNET delays for the 108 days. An envelope of trends is also drawn in Figure 4 to indicate different level of NAS operational efficiency. For instance, 'A' indicates a poor operational efficiency compared to 'B', since it reaches its operational capacity at much lower WITI counts; whose unit is the number of aircrafts, and yet renders same level of delays. Therefore, 'A' is considered the poor operational efficiency, 'B' the optimal, and 'C' the average. Furthermore, as indicated in Eq. (4), one may observe from Figure 4 a linear relationship between the WITI and the delay when both are low (that is, good weather results in less delay), and an exponential relationship when both are high, and eventually delay becomes very large when traffic demand reaches its capacity. This trend of behavior is commonly found in the queuing nature of traffic flow.

Summary

The main contributions of this paper are: 1) Sensitivity analysis for selection of reference traffic days, 2) NAS delay model improvement using piece-wise linear approach, 3) addition of flight cancellations in NAS delay estimation, 4) enveloping nonlinear relationships between observed NAS delays and WITI counts. The paper will present results in these areas based on NAS data for the entire 2005 convective weather period.

References

1. Lamon, K., "Aviationa System Performance and Convective Weather," The MITRE Corporation, 2005
2. Callaham, M., DeArmon, J., Cooper, A., Goodfriend, J., Moch-Mooney, D., and Solomos, G., "Assessing NAS Performance: Normalizing for the Effects of Weather," 4th USA/Europe Air Traffic Management R&D Symposium, Santa Fe, NM, 2001
3. Chatterji, G. B., and Sridhar, B., "National Airspace System Delay Estimation Using Weather Weighted Traffic Counts," AIAA Guidance, Navigation and Control Conference, San Francisco, CA, 2004

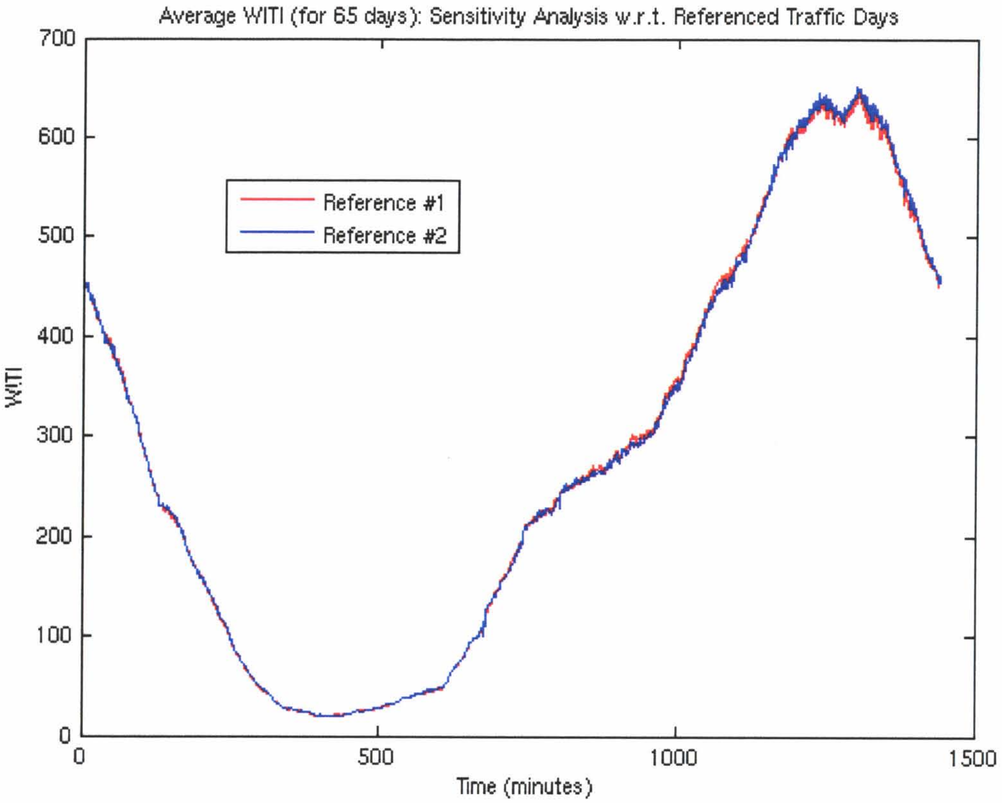

Figure 1: Time history comparison for average WITI

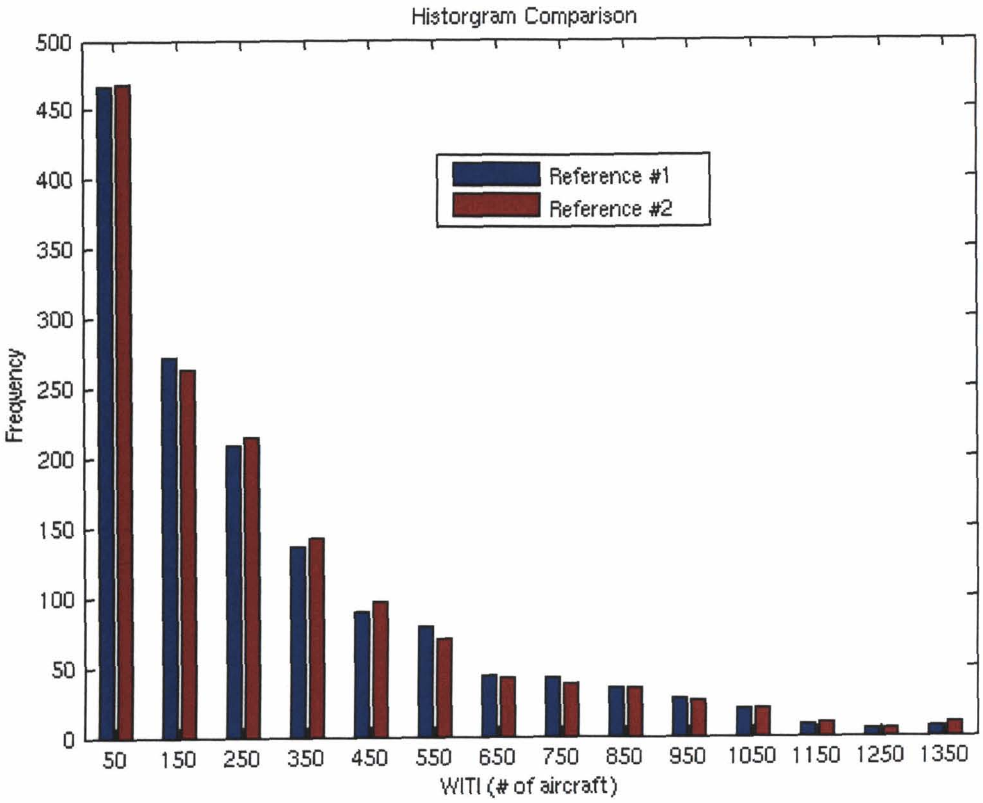

Figure 2: Histogram comparison

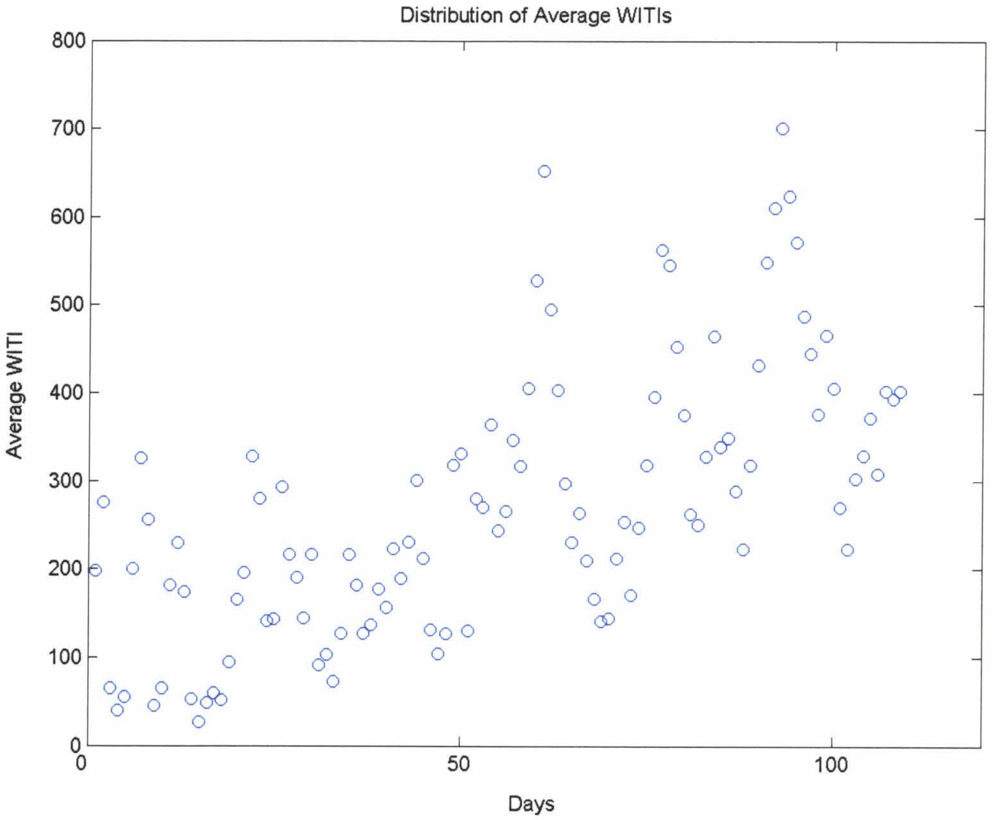

Figure 3: Distribution of average WITI

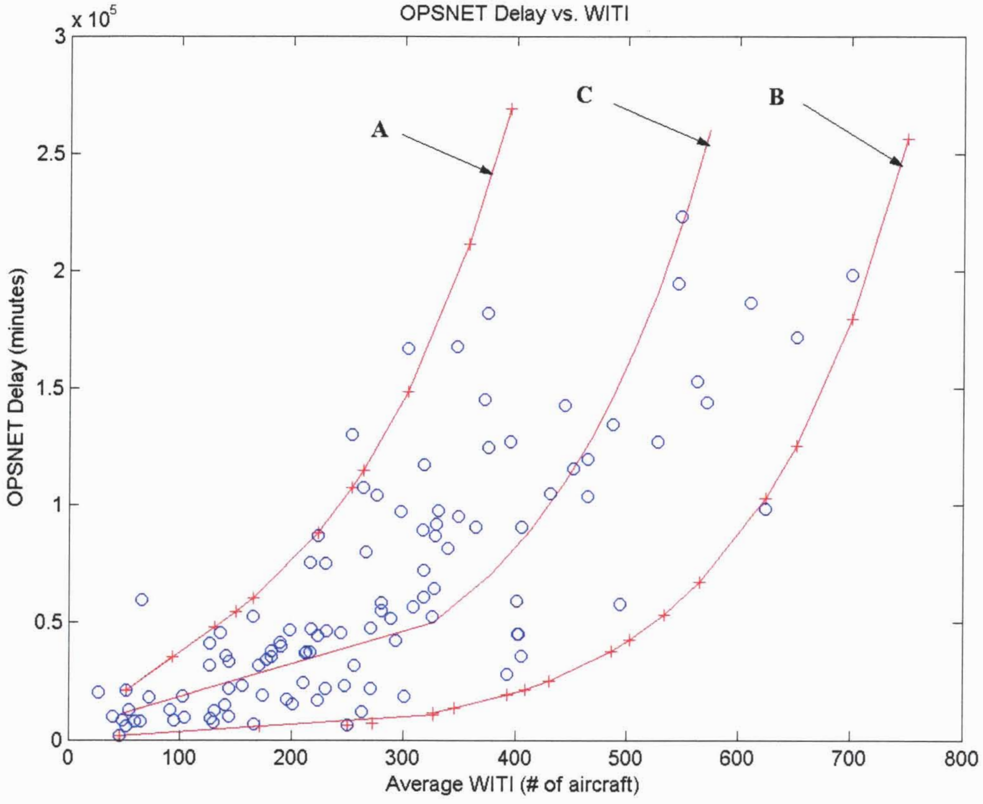

Figure 4: Variation of OPSNET delays with respect to average WITI