PREDICTION OF WEATHER RELATED DELAYS IN THE CONTINENTAL UNITED STATES

Banavar Sridhar and Deepak Kulkarni
NASA Ames Research Center, Moffett Field, CA 94035-1000

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Abstract

This paper presents models relating national delay, center level delays and weather. The method used traffic data during the spring and summer over a three-year period in the United States. The results indicate: (a) the method for estimating the delay at the national level can be extended to estimate delay at the regional level, (b) the estimation of national delay as the sum of regional delays produces a national delay estimate of comparable accuracy, while providing insights into differential impacts of regional weather on delays, and (c) the national delay can be estimated accurately by observing the behavior of 5 or 6 prominent centers.

1 Introduction

The continuous growth in the demand for air transportation results in an imbalance between airspace capacity and traffic demand. The airspace capacity of a region depends on the ability of the system to maintain safe separation between aircraft in the region. In addition to growing demand, the airspace capacity is severely limited by convective weather. Aircraft are either delayed on ground or re-routed to maintain safety. The Traffic Flow Management (TFM) methods needed to maintain safety result in increased travel times and delays in the National Airspace System (NAS). Aircraft maintenance and crew availability also lead to aircraft delays.

Of all the causes, weather has been identified as the most important causal factor for NAS delays. One of the metrics that has been used to assess the efficiency in operating the airspace is the actual aggregate delay provided through FAA's Air Traffic Operations Network (OPSNET). Therefore, to guide flow control decisions during the day of operations, and for post operations analysis, it is useful to establish a model that characterizes the relation between weather and delays. In post operations analysis the model can be used to check if the recorded delay was within the range of delays for similar weather and, if the delay is out of bounds, to examine the operations carefully for other causes. Similarly, given the expected weather, the model can be used to predict the expected aggregate delay.

Several efforts have been made to understand the connection between weather and delay. Of particular importance is the work based on the concept of a Weather Impacted Traffic Index (WITI). WITI, the number of aircraft affected by the weather at a given instant of time, was introduced in [1]. This and following studies [2-6] have established that an aggregate national weather index has strong correlation with national delays. Recent work by Sridhar and Swei [10] also shows that national delays can be modeled accurately using center level WITI. Efficient TFM decisions would benefit not just from this type of accurate modeling of expected aggregate national delays but also from accurate modeling of expected regional level delays.

The continental United States is divided into 20 geographical regions called air traffic centers. The actual pattern of center delays on a day with high national delays can help guide what kind of TFM measures should be employed. Even on days with low national delay, certain centers can have high delays requiring regional TFM.

Previous work has not addressed modeling of center level delays in terms of WITI. In contrast to the research in [10] on the modeling of national delay using center level WITI, the focus of this work is primarily to model center level delays and then explore use of the methodology to develop national delay models.

This paper presents results of an initial study of relations between national delay, center level delays and weather. The methodology is developed using traffic data in the United States for the period April to August for the years 2004, 2005 and 2006. The results presented in the paper indicate: (a) the method for estimating the delay at the national level can be extended to estimate delay at the regional level, (b) the estimation of national delay as the sum of regional delays produces a national delay estimate of comparable accuracy, while providing insights into differential impacts of regional weather on delays, and (c) the national delay can be estimated accurately by observing the behavior of 5 or 6 prominent centers.

The paper is organized as follows. The second section discusses the statistical modeling used approach in this paper. The third section discusses computation of WITI. The fourth section discusses models of center delays. The fifth section discusses two models of national delay in terms of center WITIs. The last section provides concluding remarks.

2 Delay Estimation Approach

2.1 Nature of delay and weather relationship

It is beneficial to review the qualitative relationship between traffic, weather and delay. It has been suggested in [7] that the behavior of the NAS is highly nonlinear, and days with higher delays may behave differently from those with lower delays. It should be noted that bad weather reduces the capacity of the NAS by reducing the available resources at the airport and in the airspace. In this respect, the NAS can be viewed as a queuing network. As the demand for resources as a fraction of the NAS capacity (denoted as γ) increases, the NAS delay (denoted as *d*) exhibits the following relation:

$$d \propto \frac{\gamma}{1-\gamma}, \qquad (1)$$

Where $0 < \gamma < 1$. It can be deduced from equation (1) that for low demand, the delay *d* is linearly proportional to *γ*, and for moderate demand, *d* is proportional to $\gamma + \gamma^2$. As demand reaches operational capacity, meaning as γ approaches 1, *d* increases exponentially. Furthermore, the relationship between delays and WITI described in (1) is clearly monotonically increasing. While this equation allows for qualitative insights into the nature of relationship between WITI and delays, actual data do not provide a good fit for this specific non-linear equation. Another important observation is that delays do not follow a normal distribution.

2.2 Linear and Rank-based models

In this study of center delays and national delays, two types of models have been considered: (1) rank-based models, (2) linear models. For rank based models, values of delays and WITI can be converted to ranks and then ranks can be mapped to each other. Such mapping of ranks of the two variables provides a function that can be used for predicting the delay for a given day. Rank based and linear models offer different benefits and can be useful in different ways.

To the extent linearity is violated, a linear model is going to be approximate and inaccurate. On the other hand, a monotonic relation can be modeled accurately by a rank-based linear model. Such a rank-based model would be especially better at predicting delays as compared to a linear model when violation of linearity is severe. For example, it would outperform a linear model for very high delays when the delays vary exponentially with WITI.

A rank-based model can be developed when there is a single dependent variable and a single independent variable, but it cannot be used when there are multiple independent variables. In contrast, multiple regression can be used to develop a linear model of a single dependent variable in terms of multiple independent variables. Linear models also offer the benefit of easier mathematical manipulation.

This study examines both linear and rank based models when delay is modeled in terms of a single dependent variable, whereas it examines only linear models when delay is modeled in terms of multiple dependent variables. Rank based models are characterized by Spearman's rank correlation coefficient indicating the strength of the relationship, whereas linear models are characterized by Pearson's coefficient. Parameters of linear models are identified where it is relevant to the discussion in the paper.

3 Computation of national, center level WITI

The approach used to develop an understanding of the relationship between national WITI, center WITI, center delay and national delay consists of four steps:

(1) Computation of national WITI
(2) Computation of center WITI
(3) Development of models of center delays in terms of center WITI
(4) Development of models of national delays that capture impact of each center's WITI.

This section describes the computation of WITI.

3.1 Computation of national weather impacted traffic index

WITI is an indicator of the number of aircraft affected by weather. The computation of WITI consists of: 1) assigning a value of one to every grid cell $W_{i,j}$ of the weather grid W, where severe weather is indicated and zero elsewhere, 2) counting the number of aircraft in every grid cell $T_{i,j}$, and 3) computing, X(k), the WITI at an instant of time k (at one-minute intervals) as follows,

$$X(k) = \sum_{j=1}^{m} \sum_{i=1}^{n} T_{i,j}(k) W_{i,j}(k) \qquad (2)$$

where n is the number of rows and m is the number of columns in the weather grid. The weather data consists of 7 levels. Levels, 1 through 6, indicate light precipitation, light to moderate rain, moderate to heavy rain, heavy rain, very heavy rain with the possibility of hail, and very heavy rain and hail with the possibility of large hail. Level zero indicates absence of rain. Severe weather is indicated by level three or higher. Fig.1 and Fig. 2 show severe weather and nominal traffic at 3 PM on 28 September 2004. Fig. 3 shows WITI variation as a function of time.

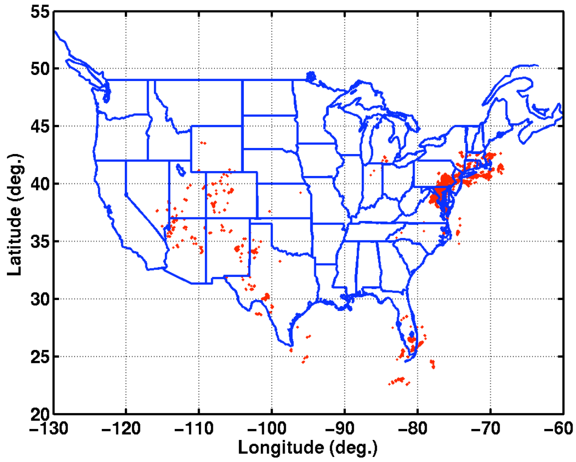

Fig. 1. Regions of severe weather at 3 PM EST on 28 September 2004

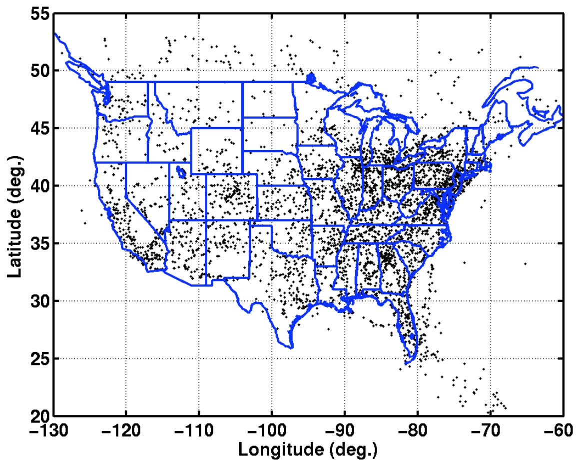

Fig. 2. Regions of expected traffic at 3 PM EST on 28 September 2004

The WITI value for a day, X, is given by the summation of WITI values that are calculated every minute

$$X = \sum_{k=1}^{1440} X(k) \tag{3}$$

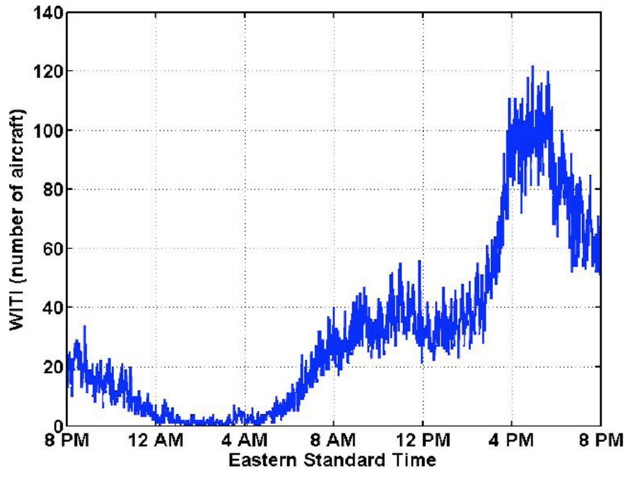

Fig. 3. WITI as a function of time on 28 September 2004

Given the WITI values for several days, a model for the aggregate national delay, δ, can be determined using the least squares procedure as

$$\boldsymbol{\delta = aX + b} \tag{4}$$

It has been shown in several studies that the national WITI linear delay model in equation (4) provides a good model to estimate national delays [2,5,6].

3.2 Computation of center level weather impacted traffic index

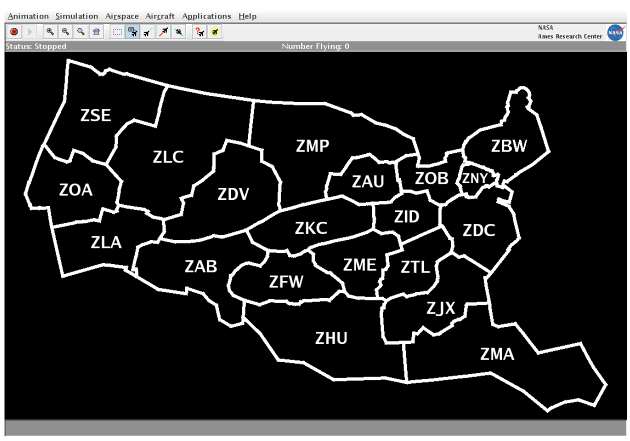

Fig. 4. Centers in the Continental U. S.

There are 20 centers within the continental U.S. Figure 4 shows their geographic locations. The center names and associated symbols are listed in Table 1. Given the center boundary, one may calculate the WITI counts within that center, much the same way as described in Eq. (2). Let B_p be the closed boundary for center p and S_p a set of all two dimensional grid cell pair (i, j) inside B_p. Then, the WITI counts for center p at time instant k can be calculated as

$$\boldsymbol{X_p(k) = \sum_{(i,j)\in S_p} T_{i,j}(k) W_{i,j}(k).} \tag{5}$$

The daily WITI value for center p, X_p, is given by the summation

$$X_p = \sum_{k=1}^{1440} X_p(k) \tag{6}$$

Figure 5 shows the variation of center WITIs during 28 September 2004.

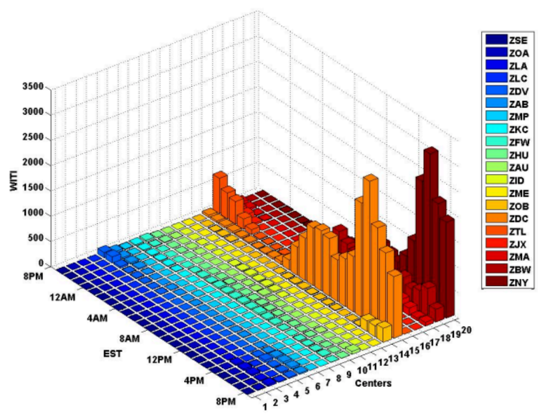

Fig. 5. Center WITI distributions on 28 September 2004

Moreover, summation of WITI counts in Eq. (4) over the entire 20 centers will render the total national WITI counts; that is, Eq. (1) can be equivalently described by

$$\boldsymbol{X = \sum_{p=1}^{20} X_p} \tag{7}$$

4. Models of Center Delays

4.1 Center delays and National WITI

The center level delay, δ_p, can be determined using the least squares procedure as

$$\delta_p = a_{pn} X + b_{pn} \qquad (8)$$

In (8), *n* refers to national as delays are being modeled in terms of X, the national WITI. The correlation of national WITI and center level delays is examined by computing Pearson and Spearman correlation coefficients between these for 500 days from the April-October, 2004-2006 period. These correlation coefficients of center delays with national WITI are shown in Table 1. Table 1 shows that national WITI has low correlation with center level delays and thus is not a good predictor of center delays. Center level delays are delays caused by a bad weather in that center. As lack of weather in one center does not imply its absence in other centers, it is not surprising that correlation between delays in one of the 20 centers and overall sum of national weather impacted aircraft is not strong.

4.2 Center delays and center WITIs

Alternatively, the center level delay, δ_p, can be estimated similar to the aggregate national delay using center WITI values and observed center delays via regression analysis and results in the equation

$$\delta_p = a_p X_p + b_p \qquad (9)$$

Pearson and Spearman correlation coefficients are computed between all center delays and all Center WITIs.

Table 1. Correlation of center level delays with national WITI and own center WITI

Center Number	Center Symbol	Center Name	National Pearson Correlation Coefficient	National Spearman Correlation Coefficient	Center Pearson Correlation Coefficient	Center Spearman Correlation Coefficient
1	ZSE	Seattle	.03	.03	-.02	.07
2	ZOA	Oakland	-.00	.06	.26	.20
3	ZLA	Los Angeles	-.06	-.03	.41	.23
4	ZLC	Salt Lake City	-.02	-.02	.42	.37
5	ZDV	Denver	.07	.12	.34	.36
6	ZAB	Albuquerque	.03	.04	.30	.07
7	ZMP	Minneapolis	.03	.12	.26	.35
8	ZKC	Kansas City	.19	.28	.44	.32
9	ZFW	Dallas Fort Worth	.19	.22	.63	.57
10	ZHU	Houston	.21	.16	.72	.47
11	ZAU	Chicago	.28	.28	.70	.56
12	ZID	Indianapolis	.25	.31	.45	.41
13	ZME	Memphis	.21	.30	.50	.44
14	ZOB	Cleveland	.29	.35	.64	.54
15	ZDC	Washington, D.C	.39	.33	.43	.42
16	ZTL	Atlanta	.37	.44	.65	.64
17	ZJX	Jacksonville	.05	.19	.17	.39
18	ZMA	Miami	.05	.11	.41	.45
19	ZBW	Boston	.25	.28	.43	.50
20	ZNY	New York	.40	.36	.70	.59

Table 1 shows the correlation between the variables (X_i, δ_i) for all the centers. It shows that center delays have good correlation with its own WITI for all centers except ZSE. Table 2 presents correlation coefficients of ZNY and ZHU delays. New York center, ZNY, is surrounded by the centers Boston, Cleveland, and Washington, DC. ZNY is separated from Indianapolis and Atlanta by another center. It can be seen from Table 2 that ZNY delay has a high correlation with ZNY WITI and the WITI of its neighboring centers. Table 2 shows that ZNY and ZHU delays have best correlation with its own center WITI and has some correlation with all or some of its neighbors. Neighboring center correlation coefficients are shown in the bold. This observation generally holds true for all centers except ZSE both for Pearson correlation coefficient and Spearman coefficient.

Given the correlation between center delays and center WITIs, equation (9) provides a simple model of center delays. Creating a more complex model, by adding other center WITIs as independent variables, increases the delay prediction only slightly. The increase is not statistically significant for the data used in this study. Therefore, center delays are modeled here using that center's WITI. One exception to this is ZSE, which is a center with very low center delays, and it can be modeled as a constant with low values.

The next two subsections take a closer look at center delay estimation for two centers, New York and Houston. The two centers correlate differently with national WITI. New York has a high correlation coefficient with national WITI and Houston, on the other hand, has a lower

Table 2. Correlation between ZNY and ZHU delays with own and surrounding center WITIs

Center Number	Center Symbol	Center Name	Pearson Correlation Center's WITI with ZNY delays	Pearson Correlation Center's WITI with ZHU delays
1	ZSE	Seattle	-.05	.05
2	ZOA	Oakland	.00	-.04
3	ZLA	Los Angeles	.05	-.05
4	ZLC	Salt Lake City	.03	-.02
5	ZDV	Denver	.04	.03
6	ZAB	Albuquerque	.00	-.04
7	ZMP	Minneapolis	-.05	-.01
8	ZKC	Kansas City	.00	.13
9	ZFW	Dallas Fort Worth	-.01	**.33**
10	ZHU	Houston	.00	**.72**
11	ZAU	Chicago	-.01	.01
12	ZID	Indianapolis	.21	.02
13	ZME	Memphis	.06	**.24**
14	ZOB	Cleveland	**.36**	.06
15	ZDC	Washington, D.C	**.48**	.00
16	ZTL	Atlanta	.13	**.10**
17	ZJX	Jacksonville	.04	**-.02**
18	ZMA	Miami	.05	**-.10**
19	ZBW	Boston	**.50**	-.01
20	ZNY	New York	**.70**	-.01

correlation coefficient with national WITI.

4.3 ZNY Delays

New York Center (ZNY) delays have a mean of 17673 minutes, and standard deviation of 19585 minutes. Pearson correlation coefficient of WITI ZNY vs. ZNY delays is .7 with 95% confidence interval to be (.6,.8). Also, if a model developed using 2004-05 data is validated against July-August 2006 data, this model (7.45 * WITI_ZNY + 10100) has a correlation coefficient of .78 with the training data and has correlation coefficient of .8 against the test data. This confirms the existence of correlation between ZNY delays and ZNY WITI.

The correlation coefficient of .7 translates into residual variance of 10736. However, the variance is heteroscedastic. Therefore, the error in the prediction depends on the value of WITI_ZNY. The heteroscedasticity makes it difficult to interpret goodness of fit without knowing the distribution of delay data in high/low/medium categories. Thus, predictive accuracy would be better interpreted by using a segmented model. Table 3 shows a three-segment model for the New York center based on dividing the center WITI values into bottom third, middle third and top third categories. The residual error for the three segments varies significantly from 7682 to 18261 showing that there is smaller error in smaller delay predictions. In contrast, prediction error estimate of a single segment model (10736) would be misleading. Overall, this model can be described as having a correlation coefficient of .72. Thus, in this case, the benefit of creating a three segment model is having reduced estimation errors in the presence of heteroscedasticity.

4.4 ZHU Delays

The Houston Center (ZHU) delays have a mean of 1799 minutes and standard deviation of 3972 minutes. Pearson correlation coefficient of WITI ZHU vs. ZHU delays is .72 with 95% confidence interval to be (.62 .82). Also, the model (1.6 * WITI_ZNY +102), developed using 2004-05 data, validated using July-August 2007 data, has a correlation coefficient of .7 with the training data and a correlation coefficient of .78 with the test data. The correlation coefficient of .7 translates into residual variance of 2109. Like in the case ZNY delays, the variance for ZHU delays is heteroscedastic and a three-segment model is provided in Table 4. Overall, this model can be described as having correlation coefficient of .75.

5 Models Of National Delay

5.1 Summation Model

In the previous section, it was shown that the best model of center delay is a multi-segment

Table 3: ZNY Delay models

WITI range	Delay Model	Residual	75th Pct Envelope	25th Pct Envelope
Low	Del= 8431	7682	Del = 9970	Del = 4698
Medium	Del= 15*WITI+7483	12820	Del= 26*WITI+8442	Del =2 * WITI + 2428
High	Del= 6*WITI+17200	18261	Del = 8* WITI + 22813	Del = 7*WITI + 3300

Table 4: ZHU delay models

WITI range	Delay Model	Residual	75 th Pct Envelope	25 th Pct Envelope
Low	Del= 558	614	Del= 700	Del= 171
Medium	Del=.6*WITI+405	1235	Del=.1*WITI+809	Del=.1*WITI+195
High	Del= 2.3*WITI-2652	4304	Del= 2.1*WITI-1365.	Del=.65*WITI - 666

model, though a single segment model provides a reasonable correlation coefficient as reflected in Table 1. While summation of multi-segment models would result in a more accurate model of national delay, it would create more complex models as compared to single segment models. Although only the summation of single segment models is examined here, this approach can be extended to multi-segment models as well. Given the models of center level delays, the national delays can simply be computed as a summation of all center level delays as in equation (10).

$$\delta = \sum_{p=1}^{20} \delta_p = \sum_{p=1}^{20} a_p x_p + \sum_{p=1}^{20} b_p \qquad (10)$$

Table 5. Coefficients of Center WITIs

Center	Weighting coefficient	95% Confidence Interval
ZAB	.9	(.7,1.1)
ZAU	5	(4.7, 5.4)
ZBW	1	(.9,1.3)
ZDC	1	(.83, 1.2)
ZDV	.5	(.4,.7)
ZFW	1.8	(1.6,2)
ZHU	1.7	(1.6,1.8)
ZID	.22	(.18,.24)
ZJX	.04	(.02,.06)
ZKC	.07	(.06,.08)
ZLA	3.5	(2.8,4.2)
ZLC	1.8	(1.5,2.2)
ZMA	.7	(.6,.9)
ZME	.17	(.15,.2)
ZMP	.4	(.3,.6)
ZNY	7	(6,8)
ZOA	2	(1.1,2.2)
ZOB	.6	(.57,.7)
ZSE	0	Not applicable
ZTL	3	(2.7,3.3)

This model will be referred to as the "All Center Model" (ACM). Table 5 shows the values of the coefficients in this equation.

It is interesting to compare this method of deriving national delays to methods that would model national delay directly in terms of national WITI, which is the approach that has generally been taken by other researchers in the past. This latter approach is described by equation (4).

The critical difference between (4) and (10) is that (4) weights the WITI in each center equally and has identical multiplier coefficient for each WITI, whereas equation (10) weights different centers differently as shown in table 5. ZNY center WITI has a weight of 7, whereas ZJX has small weights of .04. For the data used in this study, a model of national delay in terms of national WITI has correlation coefficient of .59; whereas the model (equation 10) has a correlation coefficient is .65. While the difference is not statistically significant, it seems plausible that (10) is actually more accurate given that its correlation coefficient is better than that of (4) by .06. However, more data would be needed to confirm this. The important advantage of (10) is in identifying the different contribution of WITI in different centers. For example, given a particular NAS situation, worsening weather in ZNY should be of greater concern as compared to worsening weather in ZSE.

If the goal were solely to create a predictive model of national delay, then either of these models would perform adequately. This is because errors due to equal weighting can often get averaged out in equation (4) even though WITIs in different centers have differing impact on national delays in reality. A model in (10) based on different coefficient for different center WITIs captures the underlying relation more accurately and can also be useful in situations where knowledge of the impact of regional weather on national delays is needed.

5.2 Prominent Centers Model

Next, an alternate model for national delay estimation based only on the WITI of a few centers is explored. This model will be referred to as the "Prominent Centers Model (PCM)." In the previous section the correlation between WITIs in some centers to national delays were small. The contribution of different center's

WITI to the prediction of national delay is examined in more detail in this section.

Table 6. Differential impact of different Center WITIs

Center	Average WITI	Delay Contribution	% Total Delay	% Cumulative Contribution	Corr. Coe.
ZSE	83	0	.0	0.0	.67
ZKC	1123	78	.1	0.1	.67
ZJX	1998	80	.2	0.3	.67
ZOA	79	131	.3	0.5	.67
ZLC	98	179	.3	0.9	.67
ZME	1294	223	.4	1.3	.67
ZDV	451	244	.5	1.8	.67
ZMP	749	333	.6	2.4	.67
ZID	1572	341	.7	3.1	.67
ZAB	410	357	.7	3.8	.67
ZLA	167	585	1.1	4.9	.66
ZOB	1171	748	1.4	6.3	.66
ZMA	1207	871	1.7	8.0	.66
ZBW	865	935	1.8	9.8	.66
ZFW	792	1453	2.8	12.6	.65
ZDC	1534	1571	3.0	15.6	.65
ZHU	1213	2066	4.0	19.5	.65
ZTL	2012	5947	11.4	30.9	.63
ZNY	1015	7385	14.2	45.1	.61
ZAU	1476	7703	14.8	59.8	.37

Table 6 characterizes the impact of weather in each center on NAS delays. The second column lists average daily WITI in the center. The third column lists average daily contribution of a center to national delays in model (10). The fourth column lists the ratio of this delay to the total delay as percentage. The fifth column lists cumulative contribution of this center and all centers listed above this center in the table. The last column lists the correlation coefficient of delay with WITI of this center and that of all centers listed below this center in Table 6.

It is clear from Table 6 that the majority of centers do not contribute significantly to reported delays. For example, the first 9 centers in the Table contribute only 3.8% of the national delays. Furthermore, a few of these centers can be used to predict total delays with insignificant contributions from the remaining centers. Thus, the correlation coefficient for the last 4 centers with national delay is .65 whereas that for all the centers is .67. While the exact combination of which centers to use can be varied, it is clear that a few center WITIs can be used to predict national delays. The PCM is described by the equation

$$\delta = \sum_{p=1}^{Ts} \delta_p = \sum_{p=1}^{Ts} a_p x_p + \sum_{p=1}^{Ts} b_p \qquad (11)$$

where Ts is the small subset of prominent centers chosen in the development of model. These observations agree with the results reported in [8]. In the previous work [10], Sridhar and Swei showed that national delay can be predicted well using the sum of WITIs of few centers. Here, it is shown that national delays can be modeled in terms of multiple variables in the form of WITIs of a few centers each with different weight as against the approach in [10]. Thus, in [10], all prominent centers are weighted equally whereas here those are weighted differently. Thus, the larger impact of ZNY as against ZDC is captured well.

5.3 The differential impact of weather in different centers

The differential impact of WITI in different centers on national delay can be easily understood in terms of equation (1). The derivative of delay in this equation is:

$$\left.\frac{d(d)}{d\gamma}\right|_{\gamma=\gamma_1} = \frac{1}{(1-\gamma_1)^2} \qquad (11)$$

As the ratio of demand and capacity in the clear weather situation (γ_1) is different in different centers, $\frac{d(d)}{d\gamma}$ is different as well. In congested centers such as ZNY, this derivative will be significantly higher than in less congested centers. Poor weather reduces the capacity of the NAS by reducing the available resources at the airport and in the airspace, thereby increasing γ. Therefore, $\frac{d(d)}{dWITI}$ can be expected to be higher in congested centers. Therefore, the differential impact of WITI at different centers that has been observed should be expected.

6 Summary and Concluding Remarks

This paper presents results of an initial study examining the relations between national delay, center level delays and weather. This paper is the first to create models center level delays and use them in different ways to estimate national delays. The methodology is developed using traffic data for the period April to August for the years 2004, 2005 and 2006. The results presented in the paper indicate: (a) the methodology used for estimating the delay at the national level can be extended to estimate delay at the regional level, (b) the estimation of national delay as the sum of regional delays produces a national delay estimate of comparable accuracy, while providing insights into the behavior of various regions, and (c) the national delay can be estimated accurately by observing the behavior of a few regions in the eastern part of the United States.

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