Technical Report
Agreement T2695, Task 54
Weather and Congestion

The Use of Weather Data to Predict Non-recurring Traffic Congestion

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Technical Monitor
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Sponsored by

Washington State Transportation Commission
Washington State Department of Transportation
Olympia, Washington 98504-7370

Transportation Northwest (TransNow)
University of Washington
135 More Hall, Box 352700
Seattle, Washington 98195-2700

and in cooperation with
U.S. Department of Transportation
Federal Highway Administration

September 2006

TECHNICAL REPORT STANDARD TITLE PAGE

1. REPORT NO.	2. GOVERNMENT ACCESSION NO.	3. RECIPIENT'S CATALOG NO.
WA-RD 655.1		

4. TITLE AND SUBTITLE

THE USE OF WEATHER DATA TO PREDICT NON-RECURRING TRAFFIC CONGESTION

5. REPORT DATE

September 2006

6. PERFORMING ORGANIZATION CODE

7. AUTHOR(S)

Daniel J. Dailey

8. PERFORMING ORGANIZATION REPORT NO.

9. PERFORMING ORGANIZATION NAME AND ADDRESS

Washington State Transportation Center (TRAC)
University of Washington, Box 354802
University District Building; 1107 NE 45th Street, Suite 535
Seattle, Washington 98105-4631

10. WORK UNIT NO.

11. CONTRACT OR GRANT NO.

Agreement T2695, Task 54

12. SPONSORING AGENCY NAME AND ADDRESS

Research Office
Washington State Department of Transportation
Transportation Building, MS 47372
Olympia, Washington 98504-7372
Doug Brodin, Project Manager, 360-705-7972

13. TYPE OF REPORT AND PERIOD COVERED

Technical Report

14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES

This study was conducted in cooperation with the U.S. Department of Transportation, Federal Highway Administration.

16. ABSTRACT

This project demonstrates the quantitative relationship between weather patterns and surface traffic conditions. The aviation and maritime industries use weather measurements and predictions as a normal part of operations, and this can be extended to surface transportation.

Data from two data mines on the University of Washington campus were combined to evaluate the quantitative relationship between freeway speed reduction and rain fall rate as measured by Doppler radar. The University of Washington's Atmospheric Science department maintains an archive of Nexrad radar data, and the Electrical Engineering department maintains a data mine of 20-second averaged inductance loop data. The radar data were converted into rainfall rate, and the speed data from the inductance loop speed traps were converted into a deviation from normal performance measure. The deviation from normal and the rainfall rate were used to construct an impulse response function that can be applied to radar measurements to predict traffic speed reduction.

This research has the potential to accomplish (1) prediction of non-recurring traffic congestion and (2) prediction of conditions under which incidents or accidents can have a significant impact on the freeway system. This linkage of weather to traffic may be one of the only non-recurring congestion phenomena that can be accurately predicted. This project created algorithms and implementations to correlate weather with traffic congestion. Furthermore, it may provide a means for traffic management to determine where and when to proactively place resources to clear incidents.

17. KEY WORDS	18. DISTRIBUTION STATEMENT
Weather radar, weather forecasting, traffic congestion, nonrecurrent congestion, prediction, congestion management systems	No restrictions. This document is available to the public through the National Technical Information Service, Springfield, VA 22616

19. SECURITY CLASSIF. (of this report)	20. SECURITY CLASSIF. (of this page)	21. NO. OF PAGES	22. PRICE
None	None		

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This project demonstrates the quantitative relationship between weather patterns and surface traffic conditions. The aviation and maritime industries use weather measurements and predictions as a normal part of operations, and this can be extended to surface transportation.

Data from two data mines on the University of Washington campus were combined to evaluate the quantitative relationship between freeway speed reduction and rain fall rate as measured by Doppler radar. The University of Washington's Atmospheric Science department maintains an archive of Nexrad radar data, and the Electrical Engineering department maintains a data mine of 20-second averaged inductance loop data. The radar data were converted into rainfall rate, and the speed data from the inductance loop speed traps were converted into a deviation from normal performance measure. The deviation from normal and the rainfall rate were used to construct an impulse response function that can be applied to radar measurements to predict traffic speed reduction.

This research has the potential to accomplish two very important things: (1) prediction of non-recurring traffic congestion and (2) prediction of conditions under which incidents or accidents can have a significant impact on the freeway system. This linkage of weather to traffic may be one of the only non-recurring congestion phenomena that can be accurately predicted. This project created algorithms and implementations to correlate weather with traffic congestion. Furthermore, it may provide a means for traffic management to determine where and when to proactively place resources to clear incidents.

CHAPTER 1—INTRODUCTION

The goal of this project was to demonstrate the quantitative relationship between weather patterns and surface traffic conditions. The aviation and maritime industries use weather measurements and predictions as a normal part of operations, and this can be extended to surface transportation [Moutry and Ponsford 1997; Chandra et al. 1995; Lygeros and Prandini 2002]. While it is generally asserted that there is a causal relationship between weather and transportation system delays, this relationship has not been quantified in a way that allows the effects on surface transportation systems to be predicted. This research has the potential to accomplish two very important things: (1) prediction of non-recurring traffic congestion and (2) prediction of conditions under which incidents or accidents can have a significant impact on the freeway system. This linkage of weather to traffic may be one of the only non-recurring congestion phenomena that can be accurately predicted. If the research is successful, it will create an algorithm and implementation to correlate weather and traffic congestion. Furthermore, it may provide a means for traffic management to determine where and when to proactively place resources to clear incidents.

CHAPTER 2—BACKGROUND

While it is widely accepted on an anecdotal basis that weather phenomena affect traffic congestion, little quantitative work actually has provided a statistical causal link [Luchetta et al. 1988; Aron et al. 1995; Kulmala 1997]. For example, weather radar can follow moving weather cells across a large region and even predict, with some accuracy, the expected track. If there were an accurate statistical correlation between the properties of the cell (e.g., precipitation intensity) and observed traffic disruption (e.g., non-recurring reductions in speed due to visibility or surface wetness), a traffic condition forecast (and a confidence interval for the forecast) could be calculated in advance of this type of non-recurring event. However, to accomplish this, researchers from two different fields, Atmospheric Sciences and Electrical Engineering, would need to cooperate to combine the prediction of weather cell motion and then the prediction of non-recurring congestion. Two data mines on the University of Washington (UW) campus can be used to correlate weather and traffic phenomena, the Traffic Data Acquisition and Distribution (TDAD) data mine in Electrical Engineering (EE) and the Doppler radar data mine in Atmospheric Sciences (AS). In collaboration, EE and AS investigators undertook creation of a mechanism to correlate non-recurring congestion, caused by weather, with Doppler radar data. This could be expanded to create a mechanism to use the real-time radar data to provide traffic managers with a warning of the times and locations for a probable incidents. An example of a low-resolution Doppler radar data map is shown in Figure 2.1.

Past work has created tools to correlate traffic behavior over long portions of I-5 and over the course of a whole day. For example, the speed data from sensors along I-5 north for the course of a Monday are shown in Figure 2.2. The morning recurring commute congestion appears as a valley on the plot around 7:00 to 8:00 AM. The work presented here identified days on which there were significant weather events that would likely have the effect of creating non-recurring congestion. Data for several months of traffic flow and radar data were extracted from the two data mines. These two sets of data were cross-correlated in time and space to estimate the probabilities of when and where the two data sets were correlated. This type of data fusion between disciplines may be one of the few ways that non-recurring freeway congestion can be accurately predicted. Weather is one of the few types of impacts on traffic congestion that can be predicted.

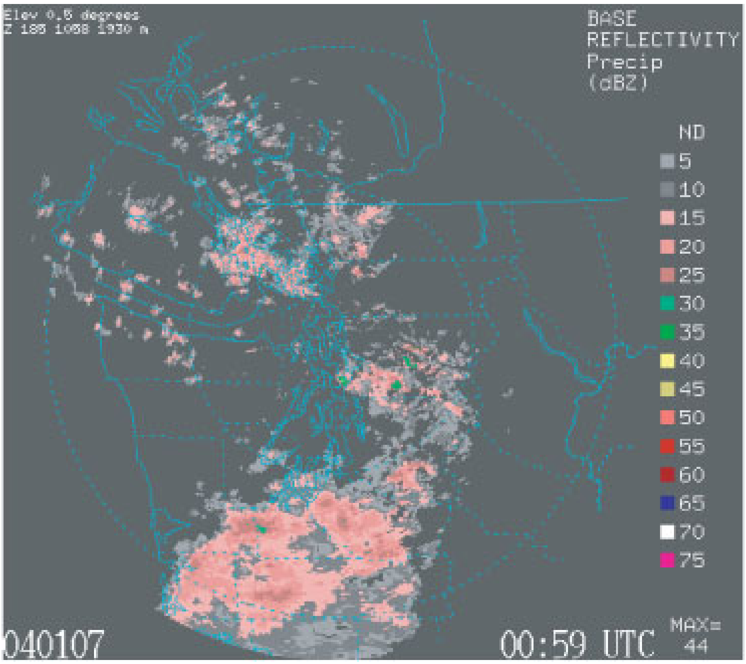

Figure 2.1: Example of low resolution radar image.

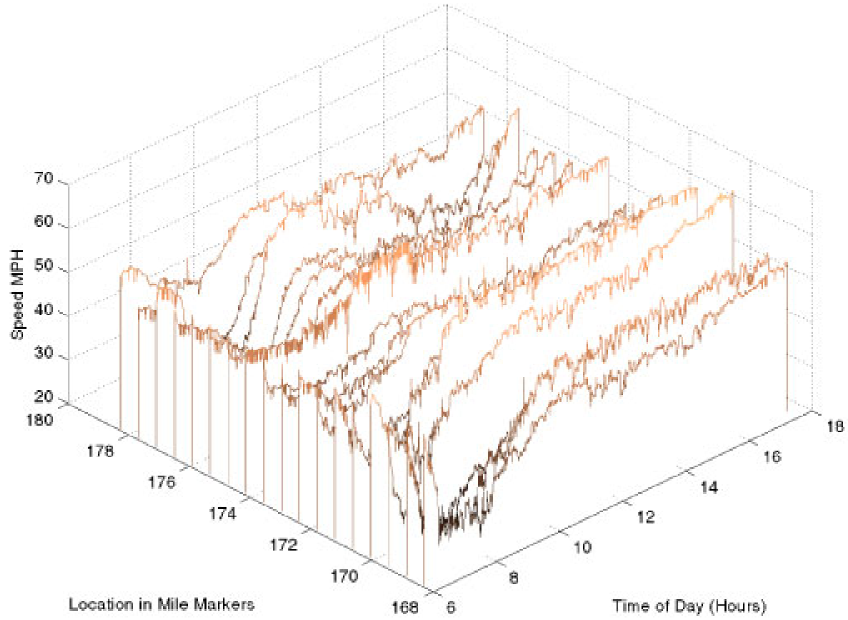

Figure 2.2: Speed at sequential locations along the I-5 corridor over the course of a Monday.

CHAPTER 3—RADAR AND INDUCTANCE LOOP DATA

The Nexrad radar used in this work is located on Camano Island, Washington. The equipment is mounted 494 ft above sea level at latitude 48 degrees 11 minutes 40 seconds and longitude -122 degrees 29 minutes 45 seconds. A full sweep of data for every range bin and angle is available every 6 minutes. The sweep is quantized into 1 degree of angle and 1 kilometer in range. A scaled representation of the location of freeway equipment cabinets and inductance loops in the sweep pattern is shown in Figure 3.1.

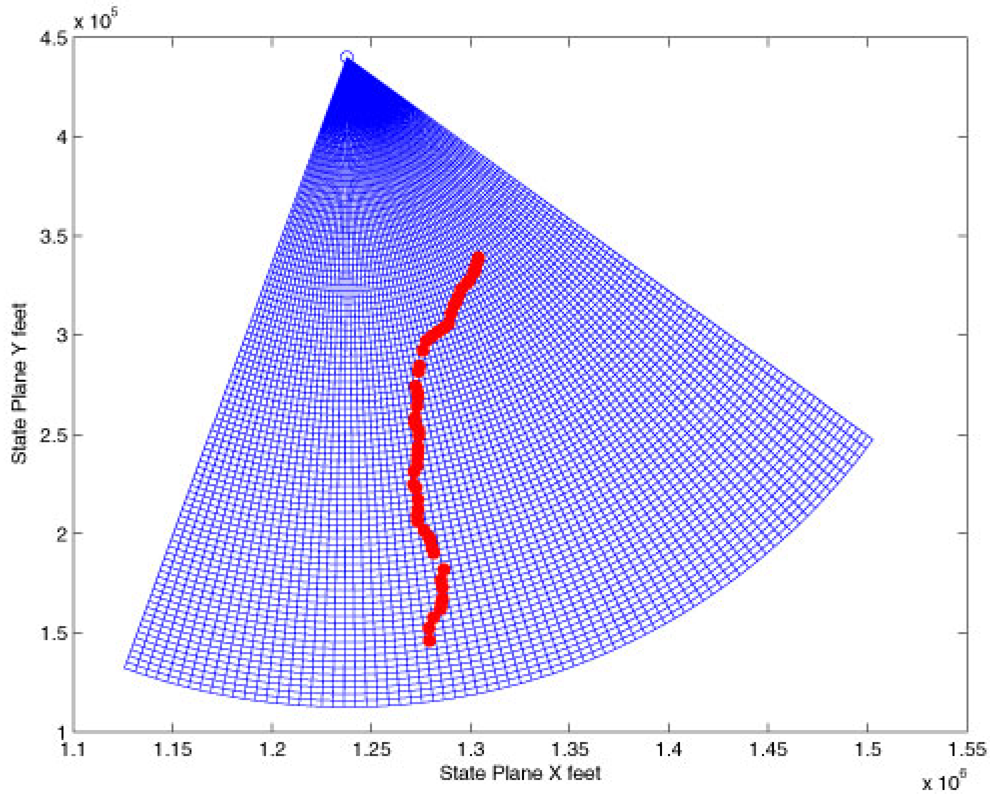

Figure 3.1: Location of I-5 inductance loop sensors in the radar scan.

A number of products/data are available from the radar. The one that was used here is the “base reflectivity.” This is measured at an elevation angle of 0.5 degrees, and the full range is approximately 230 km. It is quantized into integers from 0 to 15 representing reflectivity, or the power returned to the radar per unit of volume when precipitation or water vapor scatter the radar electromagnetic signal. These measurements are on a logarithmic scale in decibels (dB), over a range from 10 to 55 dB, and represent rainfall rates ranging from 0.1 millimeters per hour (mmh^{-1}) to over 100 mmh^{-1}.

The data from the radar are stored in a partially compressed format that is decoded with custom software. The code that performs the decompression is part of the Unix operating system, and this means that the decompression must be done under Unix. The data files, as received from the Department of Atmospheric Sciences, are arranged with one file per radar sweep that takes 6 minutes to complete. The radar operates in one of three modes: maintenance, clear air, and precipitation; only data from the precipitation mode were used in this effort.

For the work presented here, inductance loop speed trap locations were chosen in north Seattle, where there is a "convergence zone" that experiences more rainfall than other areas of Seattle. Only a limited number of speed traps are available in this area; those used in this effort are listed in Table 3.1 along with their locations in both geodetic and state plane coordinates. The SensorID field is the name used in the WSDOT Traffic Management System. The first three numbers indicate where along the highway the equipment cabinet is located, the "MS" indicates mainline southbound, and the T2 or T3 indicate whether the speed trap is in lanes 2 or 3.

By using the locations from Table 3.1, the ranges and angles to the radar were computed for each of the cabinets. Each 6-minute duration sweep of the radar begins at a slightly different angle, so each sweep had to be examined to identify the indices in the radar data that were related to the location of the loop sensors. Once this was done, the data for the seven locations from the Table 3.1 could be identified for each sweep.

Table 3.1: Speed trap names and locations

SensorID	Lat	Lon	X	Y	Location
145D_MS_T2	47.68109514	122.321248	1273922	251986	Lake City Way
145D_MS_T3	47.68109514	122.321248	1273922	251986	Lake City Way
152D_MS_T2	47.69235547	122.329574	1271951	256132	NE 88th St
167D_MS_T2	47.73350293	122.3248357	1273409	271116	NE 145th St
167D_MS_T3	47.73350293	122.3248357	1273409	271116	NE 145th St
186D_MS_T2	47.79183058	122.3160626	1275977	292347	228th St SW
186D_MS_T3	47.79183058	122.3160626	1275977	292347	228th St SW

The data associated with the locations of the speed traps were collected into a time series for the entire duration of a day. Note that the radar operates on Coordinated

Universal Time (UTC) time, and thus the “day” begins at 16:00 PST. The loop data for the same day period was extracted from the TDAD database. These two time series, loop and radar, were the basis for the quantitative comparison of the weather and the traffic. The next section provides a theoretical basis for that comparison.

CHAPTER 4—THEORY

The goal of this project was to demonstrate the quantitative relationship between weather patterns and surface traffic conditions. While it is generally asserted that there is a causal relationship between weather and transportation systems delays, this relationship has not been quantified in a way that allows effects on surface transportation systems to be predicted. We obtained several years of NexRad radar data from the Department of Atmospheric Sciences, and we obtained matching roadway data for many stations in North Seattle from the TDAD data mine.

A theoretical framework was developed to quantitatively compare these data. The measured traffic speed, $\hat{y}$ (t), where t is time, is modeled as the output of a linear system, as shown in Figure 4.1. It is the sum of three input components: (1) the "normal" traffic pattern, $\bar{y}(t)$, where examples for the loops under consideration are found in Figure 4.2, (2) the contribution to slowing from the rain fall rate, $r(t)$, and (3) all other contributions, $z(t)$

$$\hat{y}(t) = \bar{y}(t) + z(t) - \int h(\tau) r(t-\tau) d\tau. \quad (1)$$

where τ is a placeholder variable of integration and h is the "impulse response function" in linear systems theory. This is a standard textbook linear systems relationship [Bendat and Piersol 1986] and can be thought of as a "Black Box" model for the response of traffic to rainfall rate. While this is an approximation, it provides a mechanism to quantitatively relate the rainfall rate to traffic slowing. The impulse response function, h, is convolved with the rainfall rate, r (the integral in equation (1)) to estimate the contribution of rainfall to slowing. While h is not known *a priori*, a framework was created to estimate this function so that it could be used to predict the effects of weather on traffic.

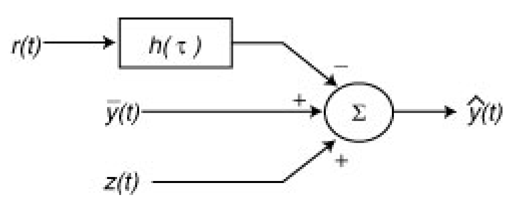

Figure 4.1 System model for identifying impulse response function for traffic slowing.

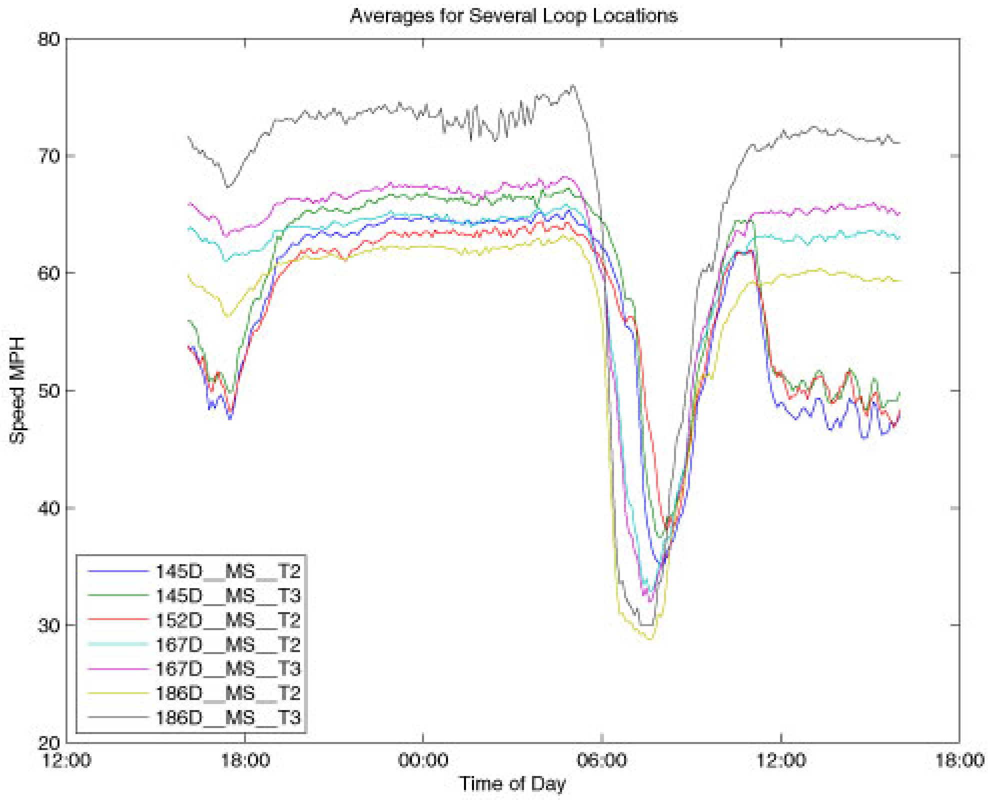

Figure 4.2. One year average, or normal speed, as a function of time of day for the loops used for comparison with radar data.

The radar reflectivity in dB, not rainfall rate, was the actual measurement available from the radar. These measurements were converted to rainfall rates at the inductance loop sensor locations. The rain fall rate was estimated from the Doppler radar reflectivity by using

$$r = \frac{1}{a}\left(10^{\frac{dB}{10}}\right)^{\frac{1}{b}}, \qquad (2)$$

where a and b are site specific and dB is the measured radar reflectivity index. These parameters were taken as $a = 200$ and $b = 1.6$ from page 25 of Seliga [1997]. This relationship is non-linear, as shown in Figure 4.3.

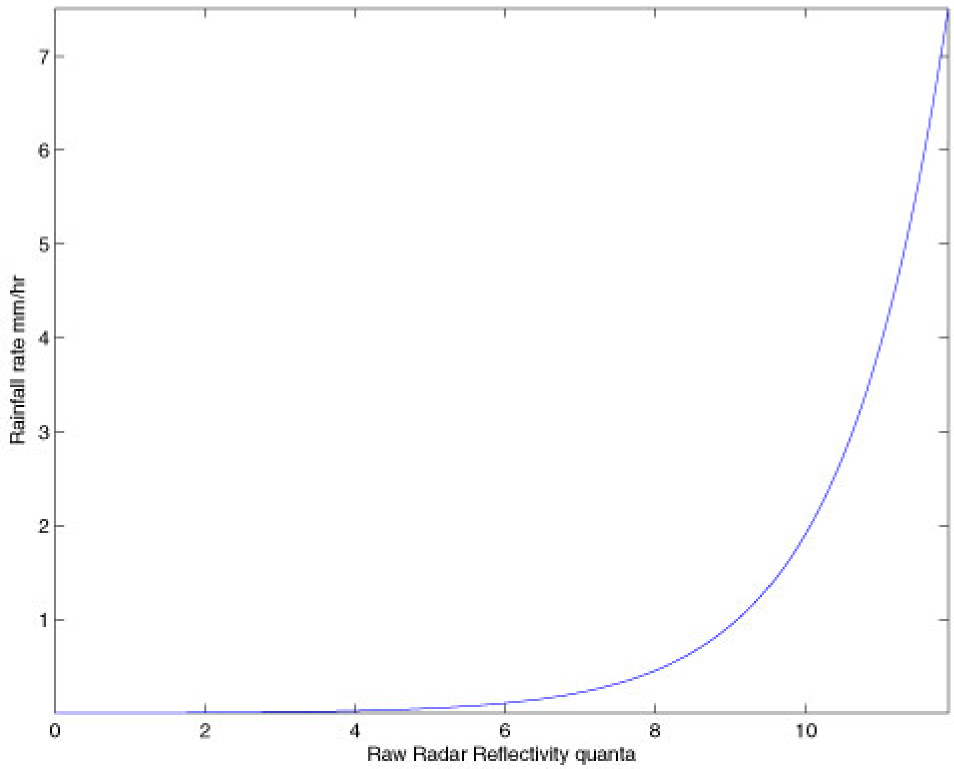

Figure 4.3: Relationship between rainfall rate and radar raw data.

To estimate the speed deviation, $\delta(t)$, from normal, $\bar{y}(t)$ is subtracted from both sides of equation (1) to get

$$\delta(t) = \hat{y}(t) - \bar{y}(t) = z(t) - \int h(\tau) r(t-\tau) d\tau. \qquad (3)$$

The rainfall rate is related quantitatively to the speed deviation by means of an impulse response function, h. To obtain an estimate of h, equation (3) is Fourier transformed,

$$\Delta(f) = Z(f) - H(f) R(f), \qquad (4)$$

where f is frequency, Δ is the Fourier transform of the speed deviation δ, R is the Fourier transform of the rainfall rate, r, and H is the Fourier transform of h, also known as the transfer function. This is post-multiplied by the complex conjugate value of $R(f)$, $R^*(f)$ to get

$$\Delta R^* = ZR^* - HRR^*, \tag{5}$$

which can be rewritten in terms of the power spectrum as

$$G_{\Delta R} = G_{ZR} - HG_{RR} \tag{6}$$

Assume that the "other" contributions and the rainfall are uncorrelated, $G_{ZR} = ZR^* \approx 0$, to get

$$G_{\Delta R} \approx HG_{RR} \qquad \text{implying,} \qquad H \approx \frac{G_{\Delta R}}{G_{RR}}. \tag{7}$$

Therefore, h is approximately the inverse Fourier transform of

$$\frac{G_{\Delta R}}{G_{RR}}. \tag{8}$$

This provides an estimate of the impulse response function, h, and allows for the estimation of the impact of rainfall on traffic by using equation (3).

To construct h, observations where rainfall was affecting traffic needed to be identified. We used the coherence function between the observed speed deviation and the rainfall,

$$\gamma^2 = \frac{|G_{\Delta R}|^2}{G_{\Delta\Delta} G_{RR}}. \tag{9}$$

The coherence function can be interpreted as the portion of the output that is linearly related to the input [Bendat and Piersol 1986]. Days when the coherence was greater than 0.7 were selected for use in estimating the impulse response function, h, from equation (8).

The experiment to determine an impulse response function used one year of radar and freeway data. The locations of the freeway loops were chosen on the basis of (1) a known convergence zone in north Seattle that was expected to have an above average number of rain events and (2) locations where paired inductance loops were available to measure speed. The "average" speed as a function of time of day for various loops in north Seattle is shown in Figure 4.2. The dates and inductance loops used to compile the estimate of h are listed in Table 4.1.

Table 4.1: Speed trap names and dates

Name	Year	Month	Day
145D_MS_T2	2004	1	28
145D_MS_T2	2004	1	29
145D_MS_T2	2004	2	29
145D_MS_T2	2004	3	4
145D_MS_T2	2004	5	8
145D_MS_T2	2004	5	28
145D_MS_T3	2004	1	7
145D_MS_T3	2004	1	29
145D_MS_T3	2004	2	29
145D_MS_T3	2004	3	4
145D_MS_T3	2004	5	27
145D_MS_T3	2004	5	28
145D_MS_T3	2004	5	29
145D_MS_T3	2004	7	10
145D_MS_T3	2004	8	4
145D_MS_T3	2004	9	11
145D_MS_T3	2004	10	6
145D_MS_T3	2004	11	2
152D_MS_T2	2004	1	8
152D_MS_T2	2004	1	29
152D_MS_T2	2004	3	5
152D_MS_T2	2004	4	20
152D_MS_T2	2004	8	4
152D_MS_T2	2004	8	6
152D_MS_T2	2004	9	11
152D_MS_T2	2004	10	6
152D_MS_T2	2004	11	27
152D_MS_T2	2004	2	27
152D_MS_T2	2004	3	5
152D_MS_T2	2004	3	26
152D_MS_T2	2004	4	14
167D_MS_T2	2004	5	27
167D_MS_T2	2004	8	6
167D_MS_T2	2004	8	22
167D_MS_T2	2004	9	11
167D_MS_T2	2004	10	6
167D_MS_T2	2004	11	27
167D_MS_T3	2004	1	7
167D_MS_T3	2004	1	30
167D_MS_T3	2004	2	27
167D_MS_T3	2004	3	5
167D_MS_T3	2004	3	25

167D_MS_T3	2004	3	26
167D_MS_T3	2004	5	27
167D_MS_T3	2004	8	6
167D_MS_T3	2004	8	22
167D_MS_T3	2004	9	11
167D_MS_T3	2004	10	6
167D_MS_T3	2004	11	18
167D_MS_T3	2004	11	27
186D_MS_T2	2004	1	7
186D_MS_T2	2004	1	30
186D_MS_T2	2004	2	27
186D_MS_T2	2004	3	24
186D_MS_T2	2004	3	26
186D_MS_T2	2004	8	22
186D_MS_T2	2004	9	1
186D_MS_T2	2004	11	27
186D_MS_T3	2004	1	7
186D_MS_T3	2004	1	8
186D_MS_T3	2004	2	27
186D_MS_T3	2004	5	27
186D_MS_T3	2004	8	22
186D_MS_T3	2004	9	1
186D_MS_T3	2004	11	18

The impulse response function, determined by using data from the year 2004, is shown in Figure 4.4. The peak at approximately 1 hour indicates that a decrease in traffic speed is most likely to occur about 1 hour after the radar identifies large reflectivity values. This suggests that the prediction horizon for the impulse response function technique, based on radar observations, is on the order of 1 hour.

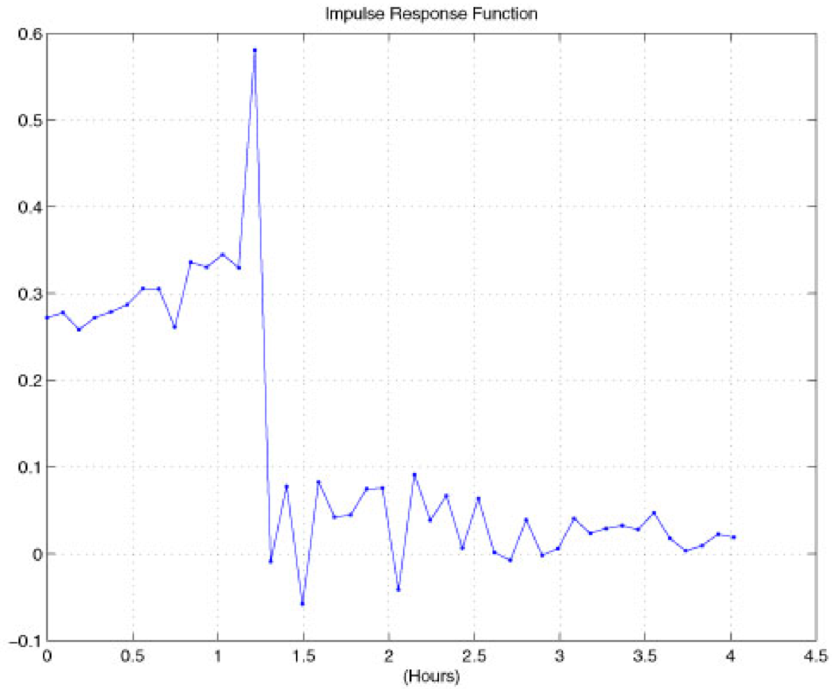

Figure 4.4: Impulse response function from 2004.

In support of the notion that the maximum impact of the rainfall rate on traffic is on the order of one hour we constructed the cross-correlations function between the deviation from normal speed and the rainfall rate,

$$\hat{R}_{\delta r}(\tau) = \frac{1}{T}\int_0^T \delta(t) r(t+\tau) dt \, , \tag{10}$$

where T is 24 hours, whose peak value is located at the delay (τ) necessary to align the two time series. Figure 4.5 is a histogram of the location of the largest peak found in the cross-correlation function for the data set listed in Table 4.1. The largest number of delay peaks is at approximately 1 hour.

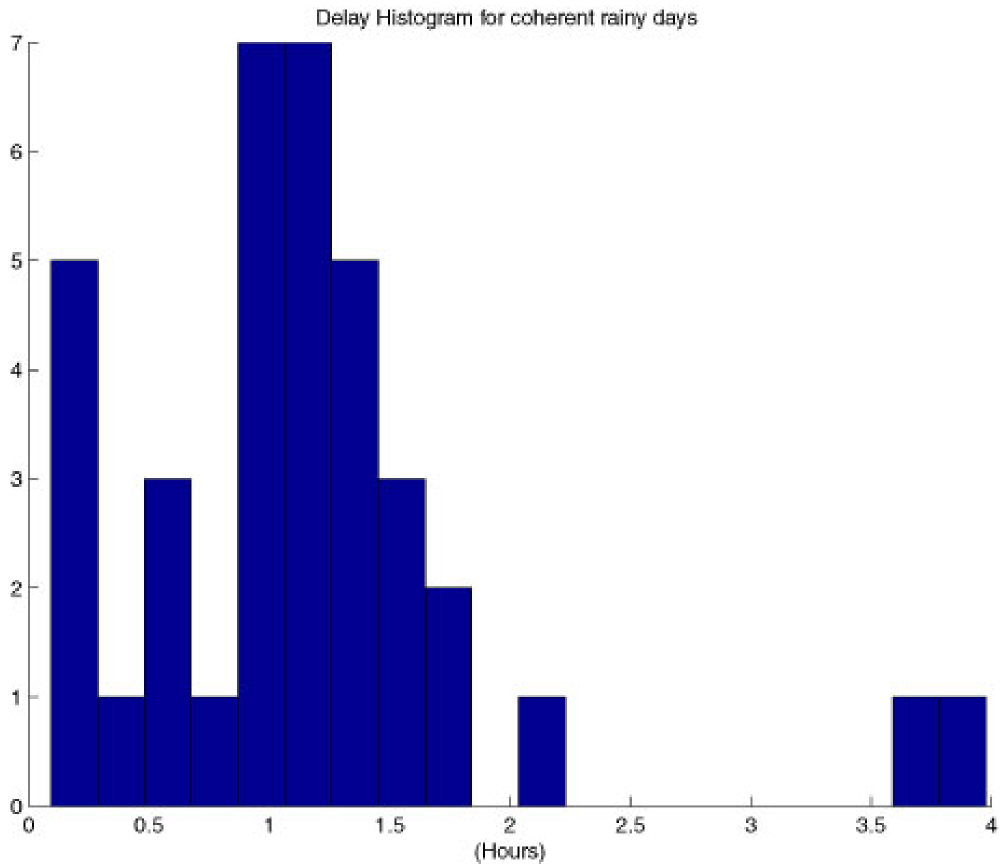

Figure 4.5: Histogram of delay peak location for the coherent rainy days in Table 4.1.

Equation (3) can be used with h to predict the slowdown of traffic due to weather conditions. The data taken from the radar are convolved with the impulse response function, h, to produce a prediction of traffic slowing. Comparisons of predicted and actual speed deviation are shown in figures 4.6 to 4.9 for four locations (ordered from south to north). At three of the four locations there were two operational inductance loop speed traps. Figures 4.6, 4.8, and 4.9 show the predictions and the observed speed deviation for two speed traps at I-5 at Lake City Way, 145th Street, and 228th Street SW, respectively. Figure 4.6 shows recurring delays at the evening and morning rush hours that are not predicted by the rainfall rate, and there is a period of slowing from 21:00 to 3:00 that is predicted by the rainfall rate. This shows that while rainfall does affect slowing, other congestion causes may outweigh the effects of weather. Figures 4.6, 4.8, and 4.9 are all from the same day, September 1, 2004, and all show the prediction derived from the rainfall rate leading observed nonrecurring slowing, which took place at night when no other external effects were acting on the traffic.

Figure 4.7 shows the single operational loop on I-5 at 88th Street and a prediction based on the methodology presented. Again, the predicted slowing temporally leads the actual slowing.

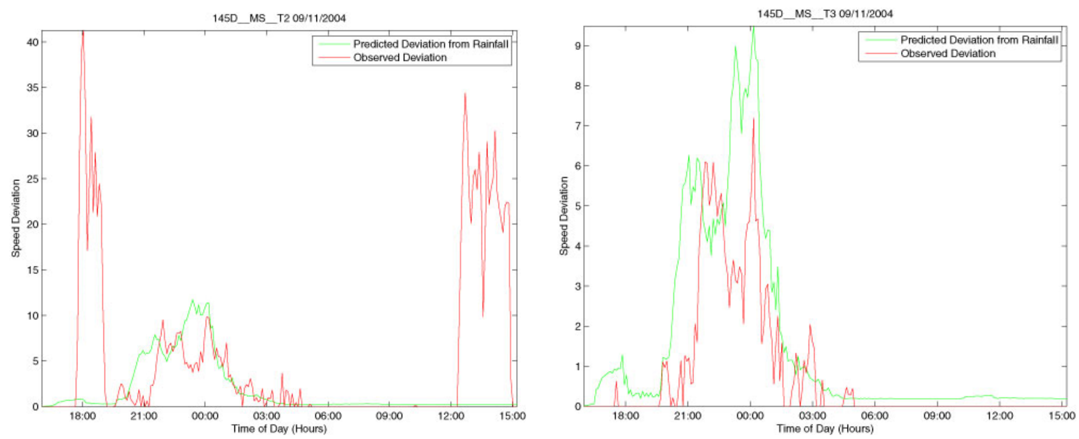

Figure 4.6: Prediction and measurement of speed deviation at Lake City Way on I-5.

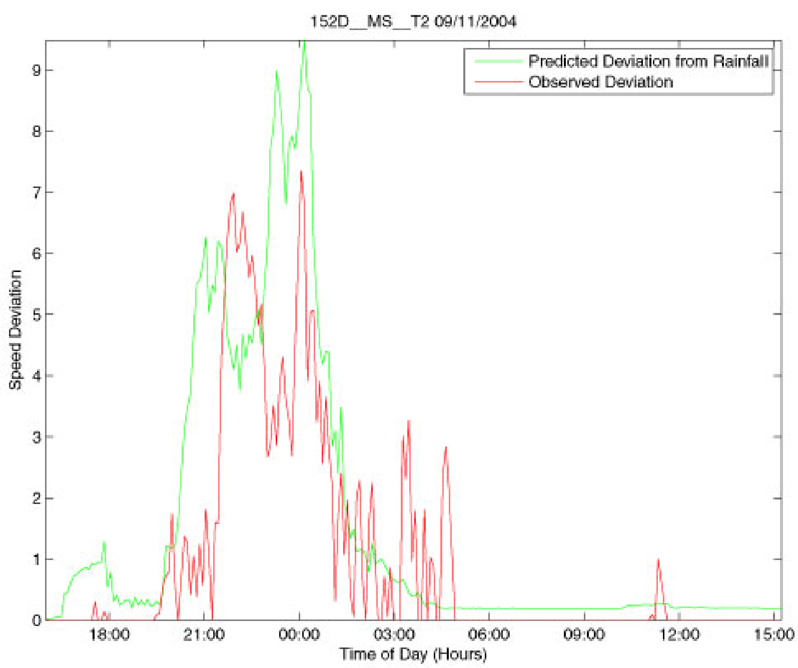

Figure 4.7: Prediction and measurement of speed deviation at 88th Street on I-5.

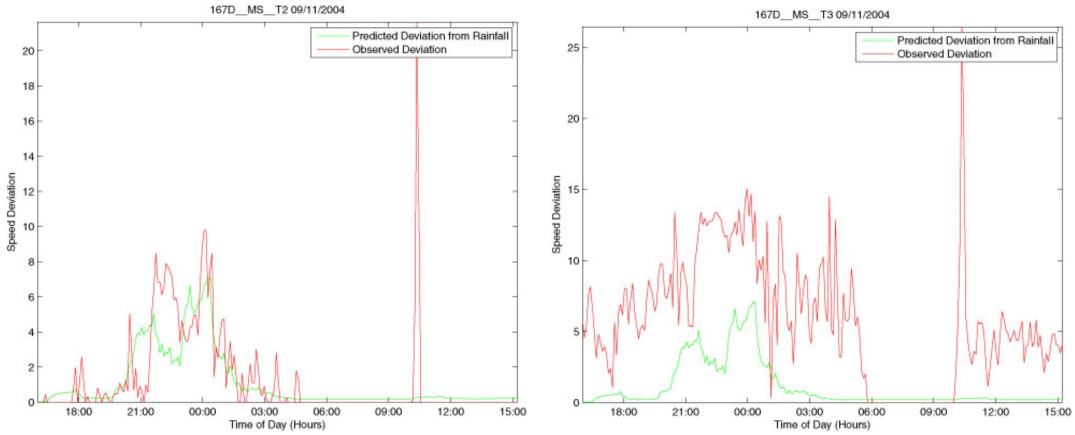

Figure 4.8: Prediction and measurement of speed deviation at 145th street on I-5.

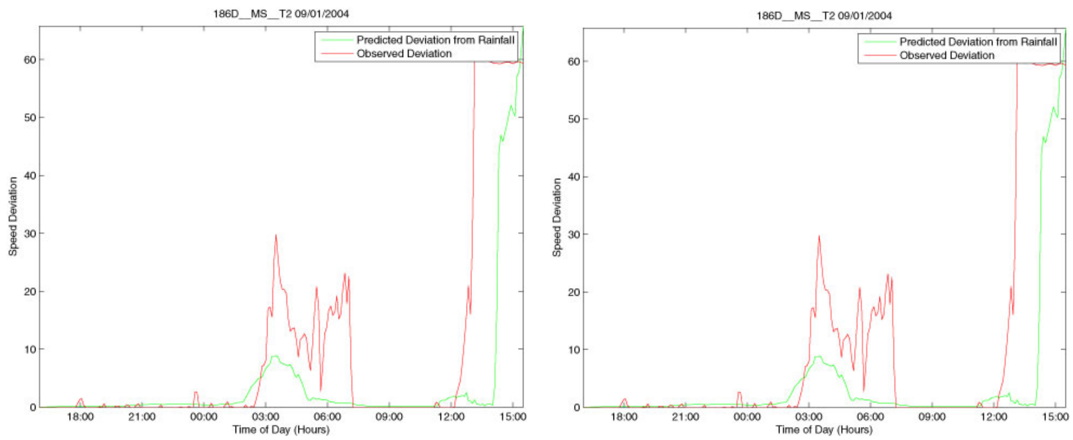

Figure 4.9: Prediction and measurement of speed deviation at 228th St SW on I-5.

CHAPTER 5—CONCLUSION

This project demonstrates the quantitative relationship between weather patterns and surface traffic conditions. The aviation and maritime industries use weather measurements and predictions as a normal part of operations, and this can be extended to surface transportation.

Data from two data mines on the University of Washington campus were combined to evaluate the quantitative relationship between freeway speed reduction and rain fall rate, as measured by Doppler radar. The University of Washington's Atmospheric Science department maintains an archive of Nexrad radar data, and the Electrical Engineering department maintains a data mine of 20-second averaged inductance loop data. The radar data were converted into rainfall rate, and the speed data from the inductance loop speed traps were converted into a deviation from normal performance measure. The deviation from normal and the rainfall rate were used to construct an impulse response function that can be applied to radar measurements to predict traffic speed reduction. The days to be used to construct the impulse response function were identified by using the coherence function. The shape of the impulse response function predicted that the largest effects on traffic will be approximately 1 hour after radar reflections of a significant scale begin.

Examples that show the relationship between the predicted slowing and the observed slowing are presented and compare favorably. However, a larger data set will provide a better evaluation. A real-time connection to the radar data should be set up, and data plus predictions should be recorded over a longer period.

This research has the potential to accomplish two very important things: (1) prediction of non-recurring traffic congestion and (2) prediction of conditions under which incidents or accidents can have a significant impact on the freeway system. This project created algorithms and implementations to correlate weather with traffic congestion. Furthermore, it may provide a means for traffic management to determine where and when to proactively place resources to clear incidents.

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