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Congestion Prediction based on NexRad Radar with Application to In-vehicle Information

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Abstract— **This paper develops a quantitative relationship between Nexrad radar reflectivity and surface traffic conditions. Data from two data mines on the University of Washington campus are combined to evaluate the quantitative relationship between freeway speed reduction and rain fall rate as measured by Doppler radar. Radar data are converted into rainfall rates and speed data from the inductance loop speed traps are converted into a deviations from a normal performance measure. The deviation from normal and the rainfall rate are used to construct an impulse response function that can be applied to radar measurements to predict traffic speed reduction. These data can then be made available in-vehicle as a new form of real-time traveler information.**

I. Introduction

This paper descibes a quantitative relationship between the U.S. Next Generation Doppler Radar or NexRad Radar 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 [1], [2], [3], [4]. 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 [5], [6]. This research attempts to predict non-recurring traffic congestion based on weather data. This linkage of weather to traffic may be one of the only non-recurring congestion phenomena that can be accurately predicted. The work presented uses a simplified impulse response function model to relate data from NexRad radar to traffic slowing using linear systems theory. While the relationship between radar reflection, rainfall rate, cumulative rainfall and surface conditions are very complex, this paper presents an attempt at a simplified model viewing radar reflections as input and traffic slowing as output. It does this using statistical methods based on a year of detailed measurements of both radar and traffic parameters. Based on the quantitative relationship between the measurements examined, and an in-vehicle travel information framework is described.

II. Background

While it is widely accepted on an anecdotal basis that weather phenomena affect traffic congestion, little quantitative work actually provides a statistical causal link [7], [8],

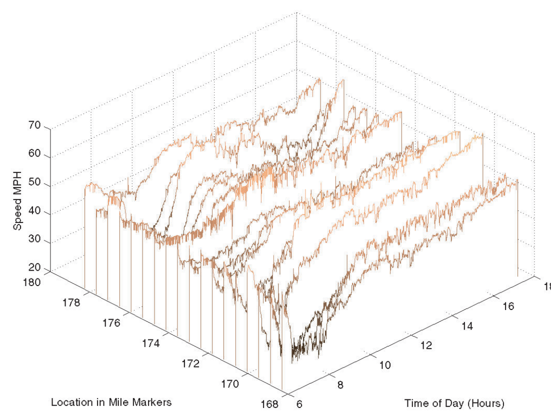

Fig. 1. Speed at sequential locations along the I-5 corridor over the course of a Monday.

[9]. For example, weather radar can follow moving weather cells across a large region and even predict, with some accuracy, the expected track [10]. 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, need to cooperate to address both the weather cell motion and the prediction of non-recurring congestion. Two data mines on the University of Washington campus are used to correlate weather and traffic phenomena. The Traffic Data Acquisition and Distribution (TDAD) data mine in Electrical Engineering [11] and the Doppler radar data collected in Atmospheric Sciences (AS) contain the raw data to undertake such a correlation.

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 1. The morning recurring commute congestion appears as a valley on the plot around 7:00-8:00 am.

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III. Radar and Inductance Loop Data

The NexRad radar used in this work is located on Camano Island, Washington. The latitude is 48 degrees 11 minutes 40 seconds and the longitude is -122 degrees 29 minutes 45 seconds and it is mounted 494 ft above sea level. A full sweep of data for every range bin and angle is available every six minutes. The sweep is quantized into one degree of angle and one kilometer in range. A scaled representation of the location of the equipment cabinets, and inductance loops, in the sweep pattern is shown in figure 2.

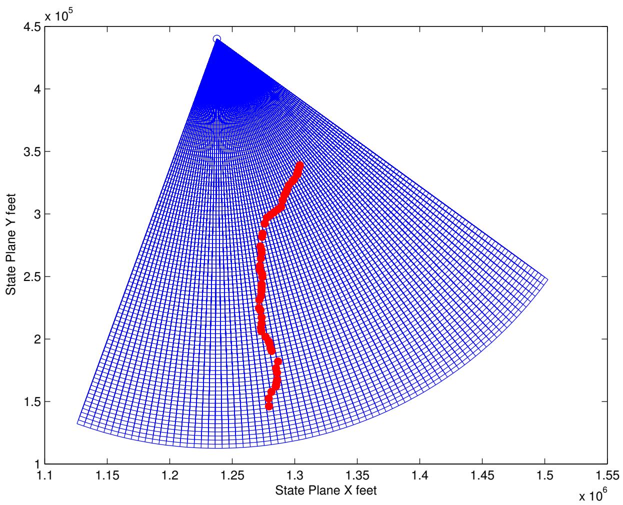

Fig. 2. Location of I-5 inductance loop sensors in the radar scan.

There are a number of products/data available from the radar. The one used here is the "base reflectivity." This is measured at an elevation angle of 0.5 degrees and the full range is approximately 230km. It is quantized into integers from 0 to 15 representing the 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 (mm h^{-1}) to over 100mm h^{-1}.

The data from the radar are stored in a partially compressed format that is decoded using custom software. The data files, as received from Atmospheric Sciences, are arranged with one file per radar sweep that takes six minutes to complete. The radar operates in one of three modes, maintenance, clear air, and precipitation. Only data from the precipitation mode is used in this effort.

For the work presented here inductance loop speed trap locations on I-5 were chosen in north Seattle where there is a "convergence zone" that experiences increased rainfall over other areas of Seattle. Only a limited number of speed traps are available in this area, and the speed traps used in the effort are shown in Table I along with the location in state plane coordinates. The SensorID field is the name used in the WSDOT TMS where the first three numbers indicate where along the highway the equipment cabinet is located, the "MS" indicated mainline south bound and the T2 or T3 indicate it is a speed trap in lanes 2 or 3. The numbers increase from south to north, and the southmost inductance loop trap is at the northern boundary of Seattle and the northmost is at the southern boundary of the city of Lynnwood WA.

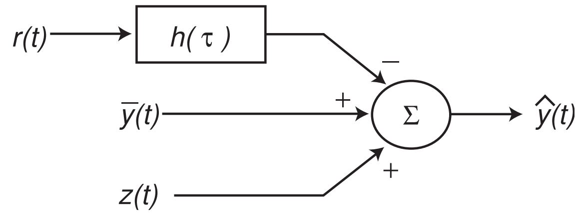

Fig. 3. System Model for identifying impulse response function for traffic slowing.

Using the location from Table I the range and angle to the radar is computed for each of the cabinets. Each six minute duration sweep of the radar begins at a slightly different angle and each sweep must be examined to identify the indices in the radar data that are related to the location of the loop sensors. Once this is done the data for the seven locations from the Table I can be identified for that sweep.

The Radar data, associated with the cell locations of the speed traps, are collected into a time series for the entire duration of a day. It should be noted that the radar operates on UTC time and thus the "day" begins at 16:00 PST. The loop data for the same day period, to be used for comparison and estimation, are extracted from the TDAD data base. These two time series, loop and radar, are the basis for the quantitative comparison of the weather and the traffic. The next section provides a theoretical basis to do that comparison.

TABLE I

Speed Trap Names and Locations

SensorID	X	Y	Location
145D_MS_T2	1273922	251986	Lake City Way
145D_MS_T3	1273922	251986	Lake City Way
152D_MS_T2	1271951	256132	NE 88th St
167D_MS_T2	1273409	271116	NE 145th St
167D_MS_T3	1273409	271116	NE 145th St
186D_MS_T2	1275977	292347	228th St SW
186D_MS_T3	1275977	292347	228th St SW

IV. Theory

A theoretical framework has been developed to quantitatively compare these data. The measured traffic speed, $\hat{y}(t)$, where t is time of day, is modeled as the output of linear system as shown in Figure 3. 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 5, (2) the contribution to slowing from the rain fall rate, $r(t)$, and (3) all other contributions, $z(t)$

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

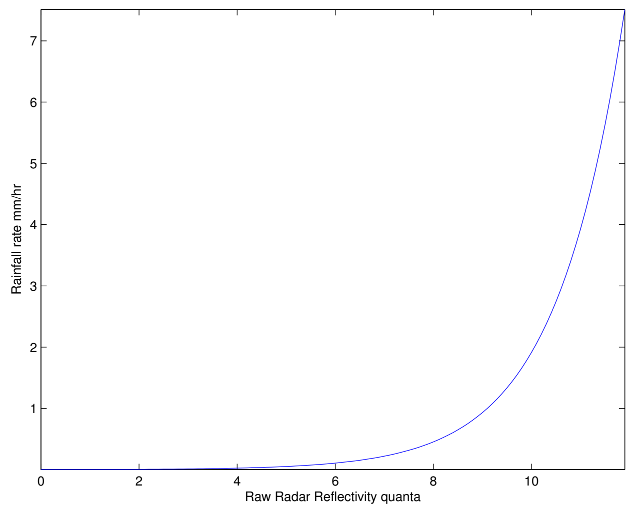

Fig. 4. Relationship between rainfall rate and radar raw data.

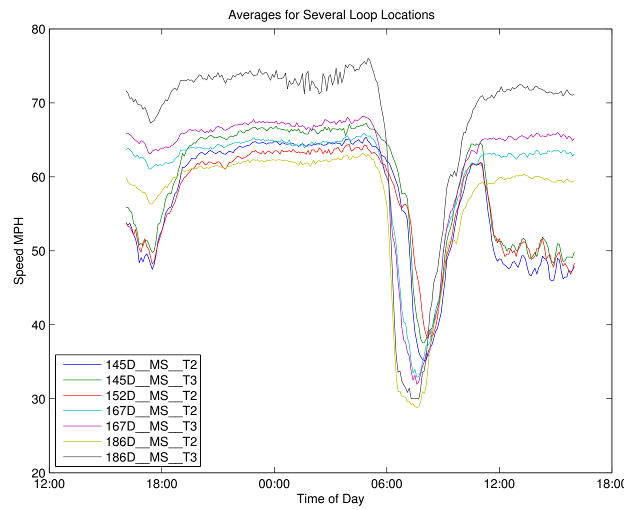

Fig. 5. One year average, or normal speed, as a function of time of day for the loops used for comparison with radar data.

where τ is a placeholder variable of integration and h is the "impulse response function" in linear systems theory. This is a standard text book linear systems relationship [12]; 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 it is the purpose of this section to create a framework to estimate this function and then use it to predict the effect of weather on traffic.

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

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

where a and b are site specific and dB is the measured radar reflectivity index. These parameters are taken as $a = 200$ and $b = 1.6$ from page 25 of [13]. This relationship is non-linear as shown in Figure 4.

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

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

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

$$\Delta(f) = Z(f) - H(f)R(f), \tag{4}$$

where f is frequency, Δ if 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. We post multiply by the complex conjugate value of $R(f)$, $R^*(f)$ to get

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

that can be rewritten in terms of the power spectrum as

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

Now assume that the "other" contributions and the rainfall rate are uncorrelated, e.g. other contributions don't change the rainfall rate, $G_{ZR} = ZR^* \approx 0$, to get

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

This approximation for the general transfer function between a signal and an uncorrelated noise term can be found in [12]. The approximation for h is the inverse Fourier transform of H,

$$h = \mathcal{F}^{-1}\{H(f)\} \approx \mathcal{F}^{-1}\{\frac{G_{\Delta R}}{G_{RR}}\}. \tag{8}$$

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

In order to estimate h observations where rainfall is impacting traffic need to be identified. We use the coherence function (γ^2) between the observed speed deviation and the rainfall,

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

as the mechanism to identify days when the rainfall is impacting traffic. The coherence function can be interpreted as the portion of the output which is linearly related to the input [12]. We select days where the coherence is greater than 0.7 as the days to be used in estimating the impulse response function h from equation (8). This enforces the assumption that the contribution of the "other" effects is minimized in the estimation of h.

Equation (8) requires estimates of the cross-power spectrum $\hat{G}_{\Delta R}$, and the auto-power spectrums $\hat{G}_{\Delta\Delta}$ and $\hat{G}_{RR}$. We use a standard averaging technique [12] to make estimates of the auto- and cross- power spectrums,

$$\hat{G}_{xy}(f) = \frac{1}{nT}\sum_{k=1}^{n} X_k^*(f,T)Y_k(f,T), \qquad (10)$$

where X and Y are the discrete Fourier transforms of the time series under consideration, f is frequency, * is the complex conjugate, T is the sample length and n is the number of samples. These estimates are used in the framework developed above to estimate h.

The experiment to determine an impulse response function was done using one year of radar and freeway data. The location of the freeway loops were chosen based on (1) a known "convergence" zone in north Seattle that is expected to have an above average number of rain events, and (2) locations where paired inductance loops are available to measure speed.

The "average" speeds, $\bar{y}(t)$ in equation (3), as a function of time-of-day for the loops in north Seattle are shown in Figure 5. Over the course of 2004 a total of thirty two days met the coherence requirement of 0.7 in equation (9) at any of the loop locations. In 2004 there were only 63 days with rainfall and fewer still with any significant accumulation, see Figure 6. When the coherence requirement is used across all the sensors the number of samples n available for use in equation (10) is 65.

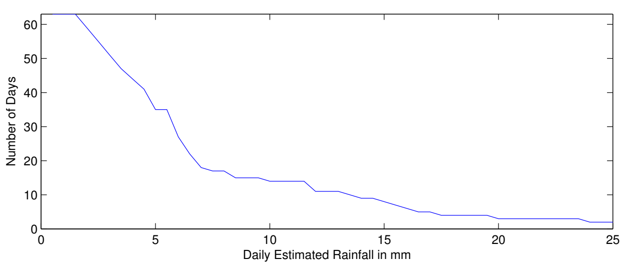

Fig. 6. Number of Days verses estimated cumulative rainfall for 2004.

The impulse response function, determined using data from the year 2004, is shown in Figure 7. The peak at approximately one hour indicates that the decrease in traffic speed is most likely to occur about one hour after the radar identifies large reflectivity values. This suggests the prediction horizon for the impulse response function technique, based on radar observations, is on the order of one hour.

To examine 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,

$$\hat{R}_{\delta r}(\tau) = \frac{1}{T}\int_0^T \delta(t)r(t+\tau)dt \qquad (11)$$

where T is 24 hours, whose peak value is located at the delay (τ) necessary to align the two time series. Figure 8 is a histogram of the location of the largest peak found in the cross-correlation function for the data set found from 2004. The largest number of delay peaks is at approximately one hour.

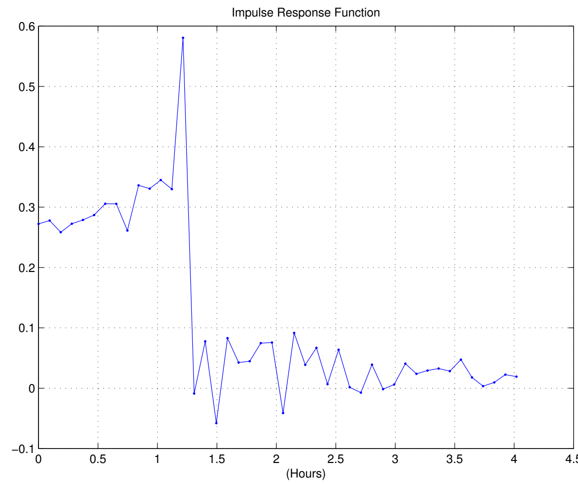

Fig. 7. Impulse response function from 2004.

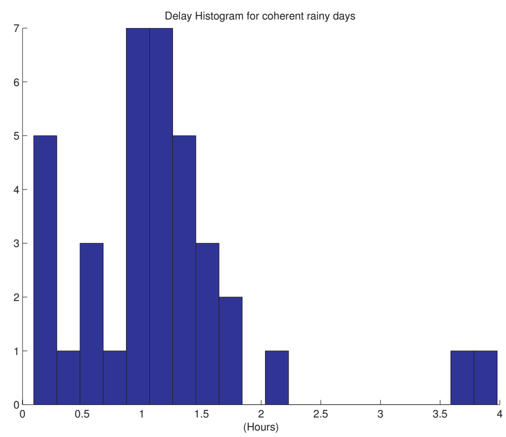

Fig. 8. Histogram of delay peak location for the rainy days with a high coherence between rainfall rate and traffic slowing.

Equation (3) can be used with h to predict the slowdown of traffic due to weather conditions. The data taken from the radar is convolved with the impulse response function h to produce a prediction of slowing of traffic. In December of 2006 a real-time data feed from the NexRad radar to the ITS lab at the UW was established. A comparison of predicted and actual speed deviation for a rainy December 25th, 2006 are shown in Figures 9 and 10 for two locations with speed traps, top and bottom, in two lanes at each site, left and right. While the prediction overestimates the speed reduction in some time periods the temporal placement of the prediction and the observed slowdowns match nicely.

Figure 11 presents data and predictions from January 2, 2007 where the left side is from I-5 at Lake City Way and the right is from the speed trap on I-5 at 88th street. In this case the prediction of time for the slowdown as well as the actual slowdown values match rather well considering that

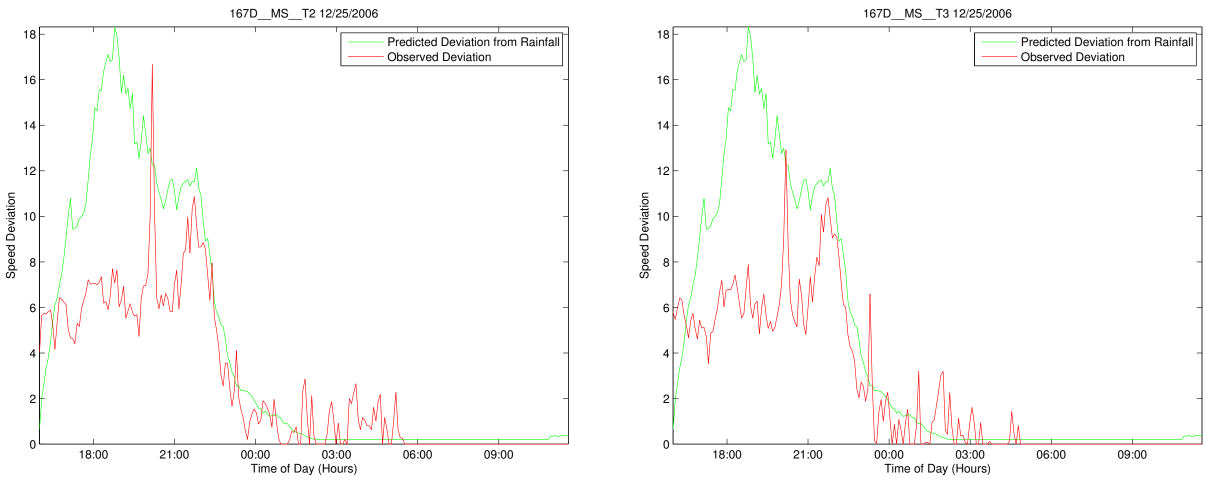

Fig. 9. Prediction and measurement of speed deviation at 145th street on I-5.

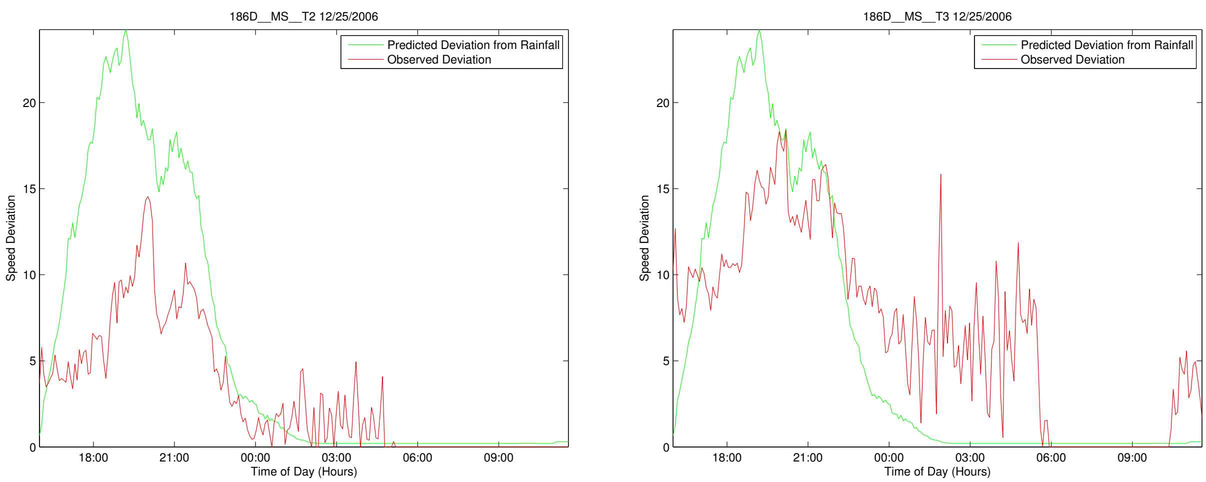

Fig. 10. Prediction and measurement of speed deviation at 228th St SW on I-5.

the prediction is from a completely independent, source the NexRad radar.

The predictive system to provide information for surface transportation operators is shown in Figure 12. It combines the real-time NexRad data with the prediction scheme described to provide a roadway delay prediction. This delay prediction is then provided to in-vehicle information systems as shown in Figure 12. This extends the combination of GIS and NexRad suggested by [14] to provide actual in-vehicle products.

V. CONCLUSION

This paper describes a method to identify the quantitative relationship between weather patterns, as sensed by NexRad radar, 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 are combined to evaluate the quantitative relationship between freeway traffic speed reduction and rain fall rate as measured by Doppler radar. Radar data is converted into rainfall rate and the speed data from the inductance loop speed traps is converted into a deviation from normal performance measure. The deviation from normal and the rainfall rate are 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 are identified using the coherence function. The shape of the impulse response function predicts that the largest effect on traffic we be approximately one 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. 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 paper describes algorithms and

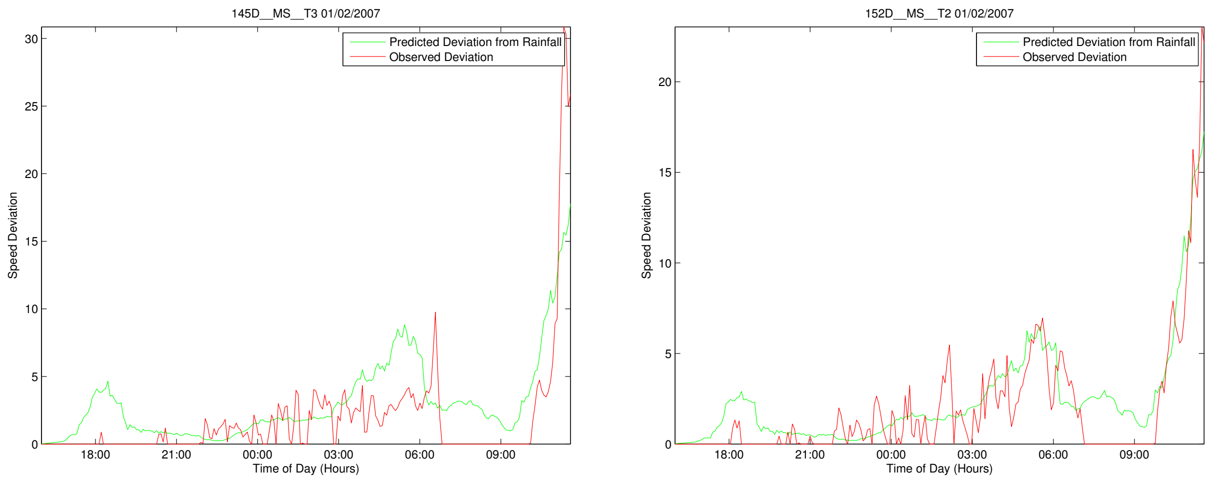

Fig. 11. Prediction and measurement of speed deviation on I-5 for January 2, 2007 at Lake City Way, on the left, and NE 88th St., on the right

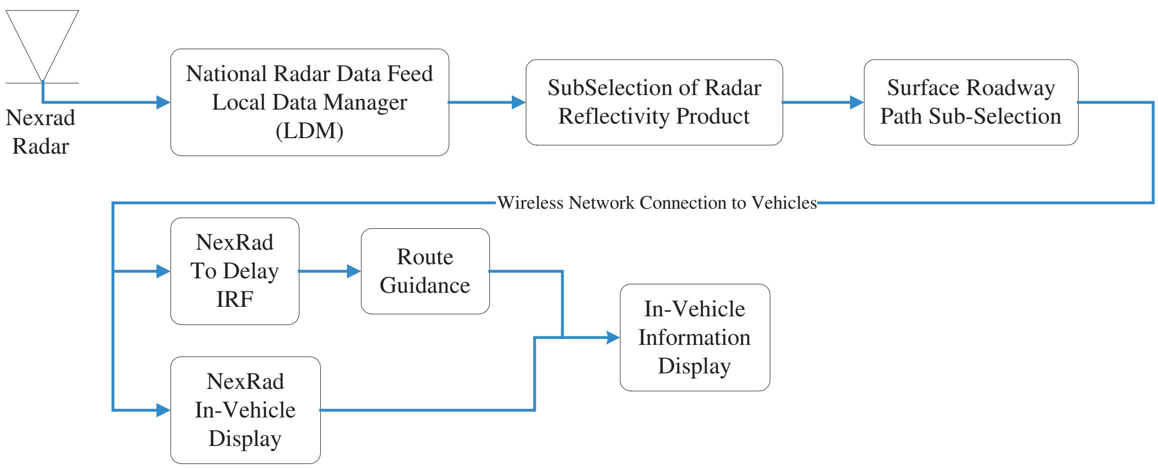

Fig. 12. In-vehicle application of NexRad Radar data.

implementations to correlate weather with traffic congestion. Furthermore, it may provide a means for traffic management to pro-actively place resources to clear incidents.

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