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16. ABSTRACT

The NEXt Generation Weather RADar (NEXRAD) program is a joint effort of the U.S. Department of Commerce, Department of Defense, and Department of Transportation for the purpose of defining, procuring, and installing a network of Doppler radars throughout the United States. The radar has been designated the WSR-88D by these agencies.

The first phase of this project concentrated on gaining access to data from the Seattle WSR-88D radar. This succeeded through the cooperation and combined efforts of the University of Washington's Department of Atmospheric Sciences (DAS) and the cognizant federal agency, the local office of the National Oceanic and Atmospheric Administration's National Weather Service (NOAA/NWS). Consequently, NEXRAD Information Dissemination Service (NIDS) Level III data were received and archived continuously by the DAS and were available for study in this project via Internet connection, computer disk, or tape.

In Phase II of this project, the use of the NEXRAD data for application to ground transportation systems was examined. The ability to derive traffic-based weather products from the NEXRAD radar measurements was established. Indices to characterize weather-related driving conditions were developed. Data on traffic flow for the I-5 Marysville to Tacoma corridor were obtained and combined with the radar-derived traffic indices. In addition to data access, the investigation examined the nature of the algorithms used by NOAA/NWS to produce the various NIDS products and developed an algorithm for point rainfall estimation that accounts for storm motion. Concepts of a storm detection, tracking, and forecasting algorithm were established as the means for future analysis and demonstrations.

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Technical Report
Research Project T9903, Task 35
NEXRAD: NEXt Generation Weather RADar—Phase II

THE NEXRAD RADAR SYSTEM AS A TOOL IN HIGHWAY TRAFFIC MANAGEMENT

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DISCLAIMER

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EXECUTIVE SUMMARY

The **NEX**t Generation Weather **RAD**ar (**NEXRAD**) program is a joint effort of the U.S. Department of Commerce, Department of Defense, and Department of Transportation for the purpose of defining, procuring, and installing a network of Doppler radars throughout the United States (Leone et al., 1989; Alberty and Crum, 1990; Crum and Alberty, 1993; Klazura and Imy, 1993; Alberty, 1992; 1993). The radar has been designated the **WSR-88D** (**W**eather **S**urveillance **R**adar, 19**88** - **D**oppler) by these agencies. Implementation of an entire network of radars at approximately 175 sites throughout the U.S. is well under way (Alberty and Fornear, 1992). Except for highly mountainous regions, coverage will include the entire country. The Seattle area radar is located approximately 60 km north of the city on Camano Island and was placed into service during the spring of 1994. The intent of this comprehensive radar system is to "...protect the lives and property of the population at large by providing timely and accurate warnings of impending severe weather. This purpose encompasses flash flood predictions, warnings of hazards to aviation, estimates of rainfall for water resource management, and the protection of military operations and installations." (Leone et al, 1989) The program is meant to provide radar measurements that will be combined with meteorological knowledge to produce reliable information on weather events that are a threat to man and his well-being. Essentially, the system overlays radar data onto computer-generated maps that show key features in a given area, automatically alerting staff when certain weather patterns appear.

Nationally, the NEXRAD radar network has thus far focused most of its applications on the detection and forecasting of meteorological phenomena with emphasis on hydrology and aviation safety (JDOP Staff, 1989; Leone et al., 1989; Weyman and Clancy, 1989; Alberty and Crum, 1990; Klazura and Imy, 1993; Bensinger et al., 1993). This project extended these applications to the development of innovative related methodologies for effective monitoring and forecasting of weather events that affect ground transportation systems. The ultimate goal is to utilize this radar-derived information within an overall system of transportation management that

will minimize weather-related safety hazards and optimize ground transportation systems, especially by reducing risks to personal injury and improving traffic flow during periods of adverse weather.

The First Phase of this project concentrated on gaining access to data from the Seattle WSR-88D radar. This succeeded through the cooperation and combined efforts of the University of Washington's Department of Atmospheric Sciences (DAS) and the cognizant federal agency, the local office of the National Oceanic and Atmospheric Administration's National Weather Service (NOAA/NWS). Consequently, NEXRAD Information Dissemination Service (NIDS) Level III data were received and archived continuously by the DAS and were available for study in this project via Internet connection, computer disk, or tape.

In Phase II of this project, the use of the NEXRAD data for application to ground transportation systems was examined. The ability to derive traffic-based weather products from the NEXRAD radar measurements was established. Indices to characterize weather-related driving conditions were developed. Data on traffic flow for the I-5 Marysville to Tacoma corridor were obtained and combined with the radar-derived traffic indices. In addition to data access, the investigation examined the nature of the algorithms used by NOAA/NWS to produce the various NIDS products and developed an algorithm for point rainfall rate estimation that accounts for storm motion. Concepts of a storm detection, tracking, and forecasting algorithm were established as the means for future analysis and demonstrations.

INTRODUCTION AND RESEARCH APPROACH

NATURE OF THE PROBLEM

Although weather is clearly the most important environmental factor affecting highway travel (Tanner, 1952), its overall relationship to ground transportation remains poorly understood (OECD, 1976; Dahir and Gramling, 1990; Harwood et al., 1987). Efforts to alleviate weather effects on transportation are undertaken as part of roadway design and maintenance, and vehicular design. Weather studies have emphasized personal safety and economic loss associated with intense storms that cause flash floods, lightning, strong winds, or threats to aviation (Kessler, 1983). Although the relationships between weather and ground transport are significant and of great concern, researche to date has clearly not given them adequate attention, even though the value of systems to deal with adverse weather effects has been demonstrated (e.g., Balgowan, 1988; Kelley, 1990). The program described herein addresses this situation and is an essential step toward not only greater understanding of weather-surface transport relationships but also toward better means of dealing with weather related problems for the benefit of society.

RESEARCH OBJECTIVES

The major purpose of this study was to develop a systematic approach for fusing and integrating Next Generation Weather Radar (NEXRAD) data into the Seattle area's Traffic Systems Management Center (TSMC). This effort encompassed investigation of the means for data acquisition, identification of relevant software, and development and evaluation of useful data-based products. The effort concentrated on utilizing standard radar products (NEXRAD Information Data Service, NIDS) (Glickman, 1993) and specially defined derivatives that relate to highway conditions and operations. The effort could potentially affect other related goals, namely, to perform correlation studies that relate weather to highway traffic and its management, the development of strategies for enhancing traffic flow and safety during adverse weather events, consideration of comparable applications to ferry operations and other public transportation

systems throughout the Seattle area, and possibly the incorporation of NEXRAD weather information into future WSDOT projects such as its Intelligent Transportation Systems (ITS) Venture Washington Program (Briglia, 1993), including the planned 1993-96 WSDOT I-90 In-Vehicle Signing and Variable Speed Demonstration Program (Pietz and Senn, 1993). It is also clear that the transfer of the research findings to other metropolitan areas of the country where traffic and highway operations are significantly linked to weather conditions may be highly desirable.

BACKGROUND

WEATHER AND ITS EFFECTS ON TRAFFIC

Most of the difficulties that occur during weather-related accidents are due to precipitation events. Wet pavement reduces the friction between the tire and road surface, causing a reduction in tire traction. This can lead to hydroplaning and the potential for skidding. An additional hazard of driving in the rain is a loss of visibility caused by both the rainfall itself and associated splash and spray from other vehicles.

Figure 1 (National Transportation Safety Board, 1980; Dahir and Gramling, 1990) shows the percentage of wet time for each of the contiguous 48 states. These times range from a maximum of 7.1 percent in Vermont to a minimum of 1.1 percent in Arizona. The state of Washington ranks eighth nationally, but given the climatological difference between the eastern and western regions of the state, it is clear that the largest population, which resides in the Puget Sound area, is at significantly greater risk than these statewide data suggest, possibly by as much as a factor of two. That is, the fraction of wet time in the western region is considerably greater than that in the eastern region, and consequently, the risk of precipitation-related fatalities in the west is greater than almost anywhere in the entire country (based on the statistical increase in fatalities associated with wet pavement conditions in comparison to dry conditions). Figure 2 illustrates the corresponding percentage of fatal accidents that occur on wet pavements in each of the same states. Note that the state of Washington ranks number one in this category; this is a significant difference in comparison to the rest of the nation, although neighboring Oregon produces a similar figure.

The discrepancy between the rest of the nation and Oregon and Washington is most likely associated with the significant climatic differences between western and eastern regions of these states. That is, the greatest number of people reside in the western regions of these two states, whereas the percentage of wet pavement data reflect averages of the entire geographical regimes of the states. The effects of wet pavements on fatalities is further illustrated in Figure 3, which combines the data from figures 1 and 2. It shows the percentage of fatal accidents on wet

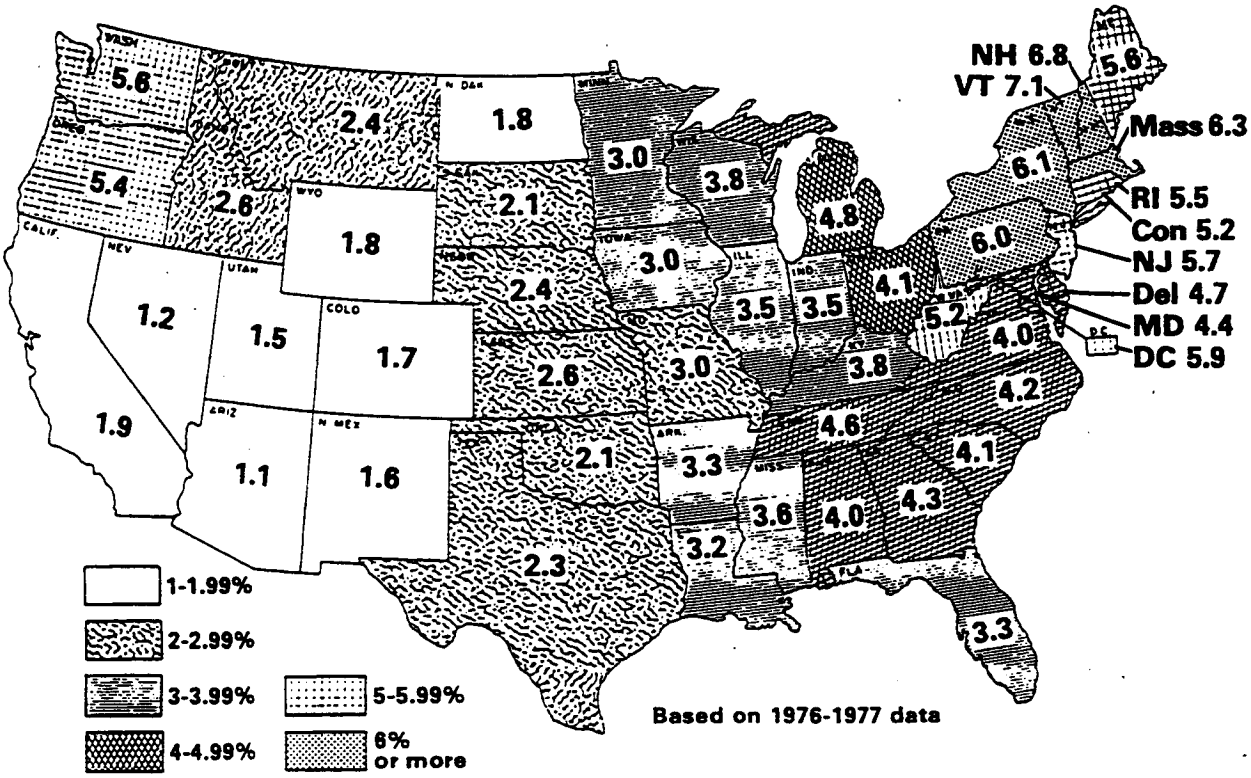

Figure 1. Percentage of wet time in each state (from NTSB, 1980).

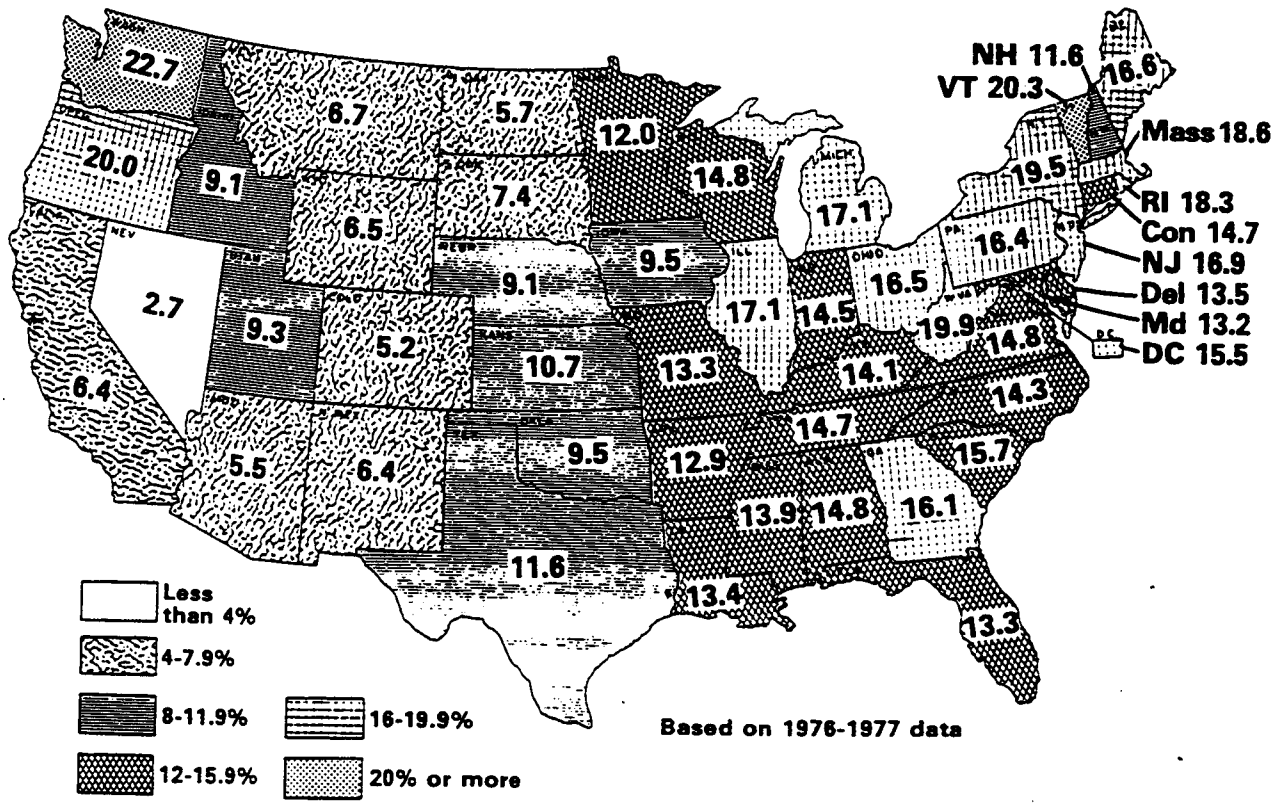

Figure 2. Percentage of fatal accidents on wet pavement in each state (from NTSB, 1980).

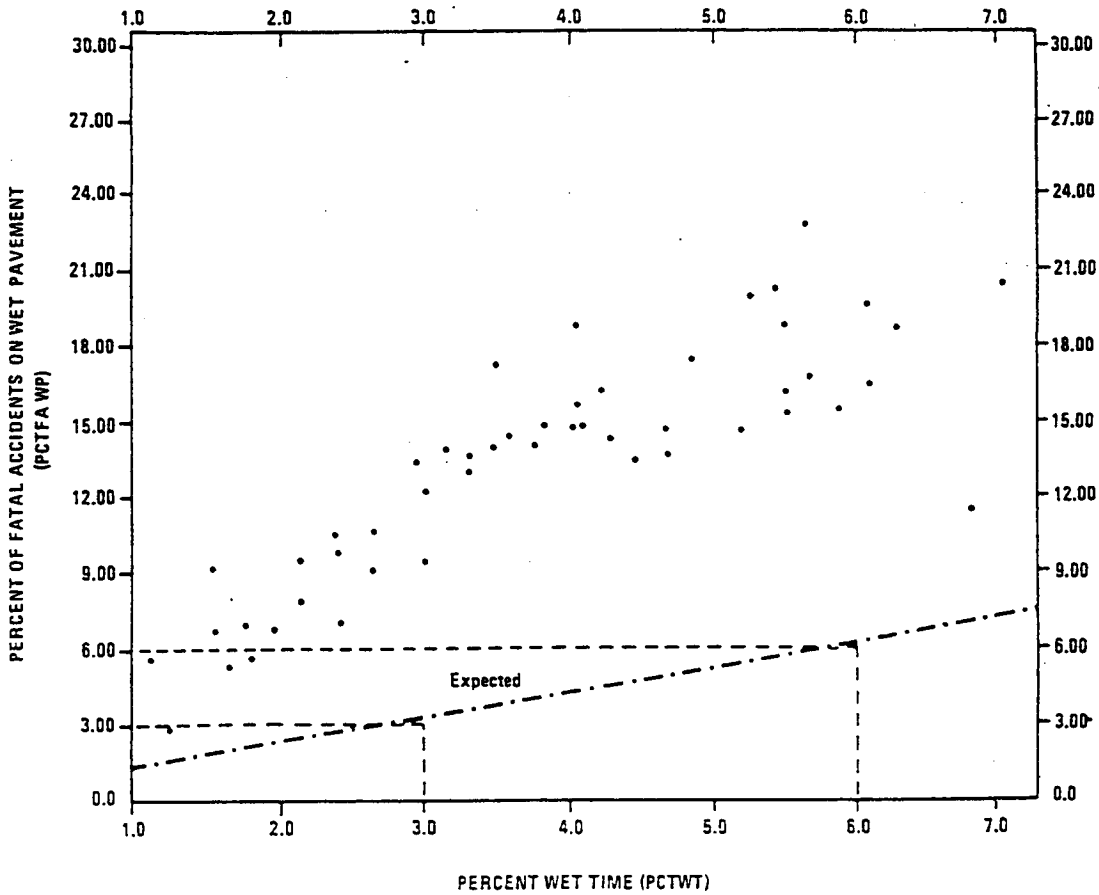

Figure 3. Plot of observed percentages of wet times and fatal accidents on wet pavements and expected values (from NTSB, 1980).

pavement as a percentage of wet time; the data clearly illustrate the major effects of wet pavements percentage of wet time; the data clearly illustrate the major effects of wet pavements on fatalities. The problem is dramatically illustrated by a comparison of the percentage of wet time (5.6 percent) in the state of Washington versus the percentage of fatal accidents on wet pavement (22.7 percent), equating to nearly four times the risk of fatalities during wet driving conditions. These results demonstrate the importance of reducing the impact of address wet pavement driving conditions on fatalities, particularly inthe regions most affected, such as the states of Washington and Oregon.

Relatively few efforts to quantify the effects of adverse weather on roadway capacity have been performed (Transportation Research Board, 1992). Two studies are relevant here: one conducted on the Gulf Freeway (I-45) in Houston (Jones et al., 1970), and the other on I-35W in Minneapolis (Ries, 1981). Both sets of observations were made on three-lane segments influenced by bottlenecks so that the history of "capacity volumes" was available. The Gulf Freeway study reported that rain significantly reduced capacity by 14 to nineteen 19 in comparison to clear weather values (with a 95 percent statistical confidence). Results from I-35W suggested that even a "trace" amount of precipitation reduces capacity by 8 percent. Each 0.01 inch per hour in rainfall results in a further decrease of 0.6 percent in capacity. When precipitation falls as snow, the impact is even greater: an additional 2.8 percent decrease in capacity for each 0.01 inch per hour of snow (water equivalent) beyond the initial "trace" decrease of 8 percent.

Consequently, it is especially important to address these conditions and to develop tactical means for dealing effectively with them in order to reduce these risks. The NEXt Generation Weather RADar (NEXRAD) provides a special opportunity to conduct a serious study of the relationship between weather and traffic flow, as well as the potential to improve driver awareness of weather conditions. The radar measurements are particularly valuable in monitoring the periods and degree of wet time that occur in the region covered by the radar.

TRAFFIC FLOW: QUALITY OF SERVICE CONSIDERATIONS

Because the Puget Sound area is often faced with saturated or near-saturated driving conditions, it is instructive to examine how quality of service is dependent on traffic demand. A qualitative illustration of this phenomenon was given by the OECD (1981) and is shown in Figure 4. The figure shows that when traffic demand is relatively low, quality of service (QOS) can be high. As demand increases, QOS normally decreases along a smooth curve, unless saturation or an unexpected event such as an accident or breakdown occurs. Such phenomena can dramatically alter the behavior of the highway system and cause a precipitous decrease in QOS. Once this type of behavior occurs, decreasing demand no longer produces system recovery along the same curve that led to the existing condition. Rather, the system follows a hysteresis-type curve, in which recovery to high levels of QOS results only after demand has returned to much lower levels. At some critical level of demand, the system is then able to recover to its normal QOS level. This well-known traffic behavior signifies that the optimum operation is possible only if conditions such as saturation and accidents are avoided. Because precipitation and other weather related phenomena (e.g., fog, high winds, road glare, and other reductions in driver visibility) are both direct and indirect factors in the QOS-demand equation, efforts to deal with such events and their consequences deserve study and, eventually, actions to reduce their impacts.

It is also instructive to ponder what might be done about the adverse effects of weather on highway operations. Several possibilities exist within the context of developing a **more effective traffic management system.** Inclusion of reliable NEXRAD-derived weather data products into existing traffic management schemes holds great promise for identifying potential weather-related problems before their occurrence and then initiating actions to lessen or avoid their occurrence. Such actions might include modulating freeway speed limits, optimizing traffic re-routing and control, communicating roadway conditions and their potential hazards to drivers, better preparing service providers (e.g., police, fire and health agencies) and better informing the commercial ground transportation system. These factors and features are discussed in more detail below.

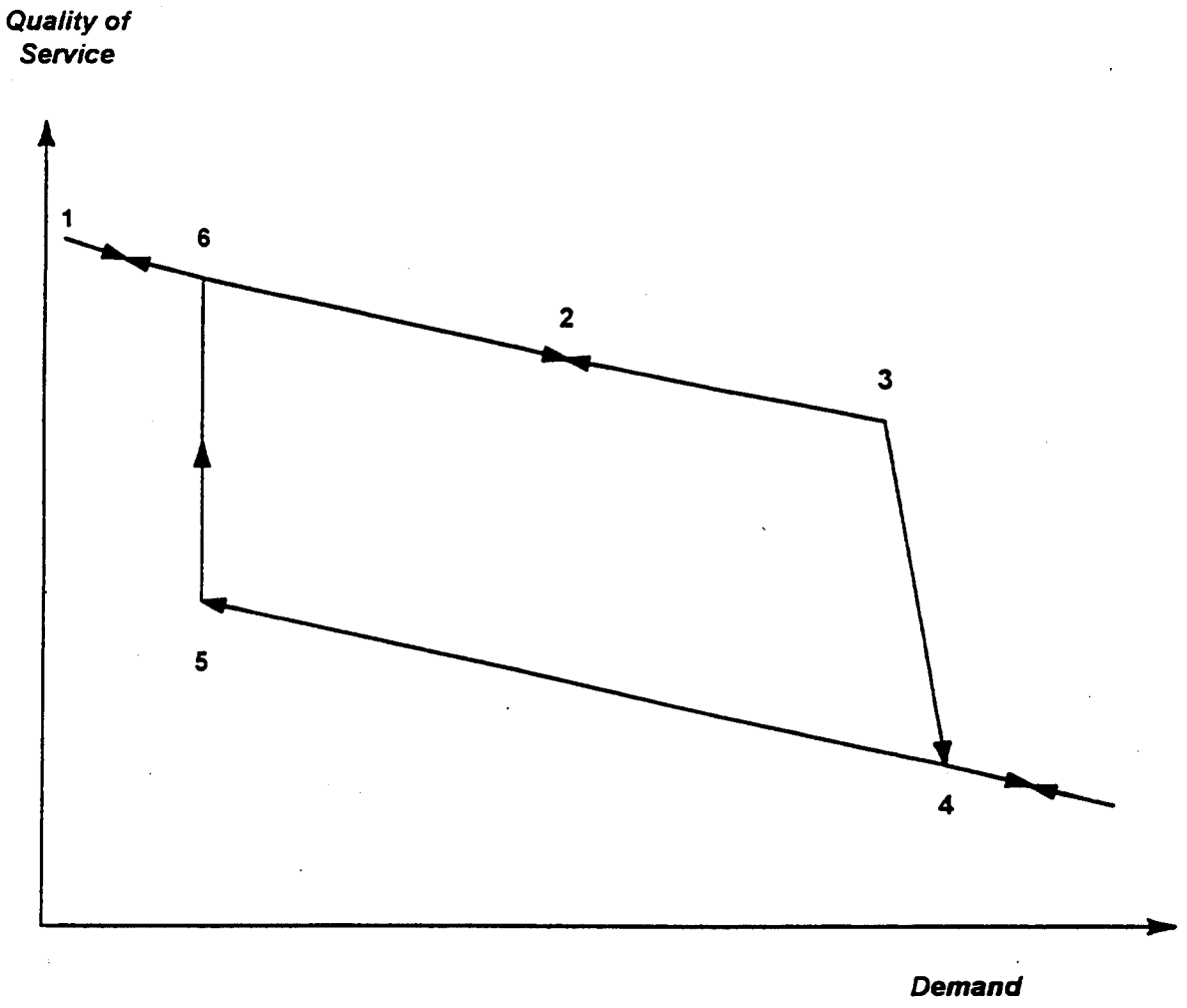

Figure 4. Dependence of quality of service (QOS) on demand, showing traffic saturation and event phenomena effects (from OECD, 1981).

Weather Data

To improve our understanding of how weather affects traffic and highway operations, we must have an accurate, reliable record of weather for comparison with ground transportation circumstances and other related factors. The NEXRAD radar will be a major resource for this purpose.

Better Understanding of Weather-Traffic Relationships

NEXRAD radar data will provide a reliable basis for discovering how weather, especially precipitation and its spatial and temporal variability, affects traffic flow in urban areas. Such understanding will contribute to management practices that will reduce congestion, improve safety, reduce costs, and improve highway designs.

Actions for Dealing with Adverse Weather

A deeper understanding of weather-traffic relationships holds potential to improve methods for dealing with adverse weather. Possibilities include automated speed limit adjustments; traffic rerouting; more effective communication of highway conditions; designation of alternative routes; accurate on-line estimates of travel times for designated routes; alerts for transportation managers, police, fire fighters, and other public safety officials of possible weather-related factors that would affect delivery of their services; and identification of engineering and environmental factors that adversely affect ground transportation. Related actions offer the potential to reduce traffic congestion, reduce accidents, save lives, save time, and improve engineered transportation systems.

Modulation of Traffic Flow

The optimum speed for vehicular freeway throughput occurs at speeds much lower than posted freeway speed limits. This is illustrated in Figure 5, which shows how the optimum flow depends on speed. The underlying reason that this condition occurs at speeds much lower than 65 mph is the dependence of the safe vehicular separation distance on speed. Essentially, this result shows that controlled modulation of speed limits during certain prescribed system conditions can result in improved performance and therefore delivery of higher QOS.

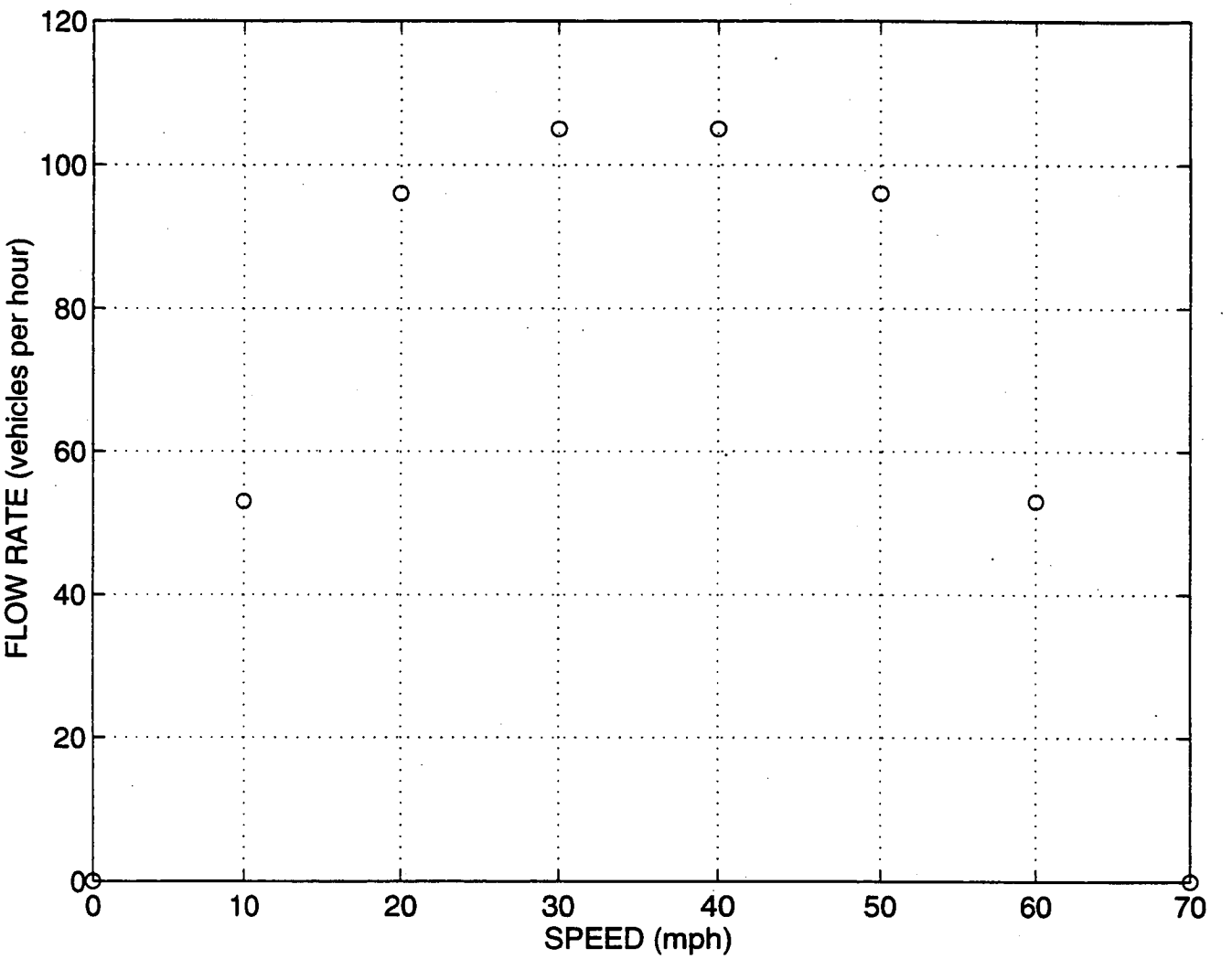

Figure 5. Dependence of vehicle flow rate on speed based on a linear speed-density relationship.

Better Informed Driving

With the continuous, highly reliable monitoring of weather information that will become available from the NEXRAD radar, the potential exists to develop communications and management systems that will give drivers reliable indications of driving conditions throughout the Puget Sound region. Such information might include indications of storm locations, their intensity, their expected duration and movement, the degree of wetness, optimum speeds for transit and/or safety, boundaries between rainfall and snowfall, and the best routes and times for avoiding adverse weather.

NEXRAD WSR-88D RADAR

Program

The U.S. is undergoing a major effort to upgrade its national weather radar system. This effort began in 1978 with the Joint Doppler Operational Project, which demonstrated the meteorological value of modern Doppler, or coherent signal processing-based technologies, at S-band (10-cm wavelength) in significantly improving radar-derived information on storms. In 1980 the National Weather Service (NWS) joined forces with the Federal Aviation Administration (FAA) and U.S. Air Force (USAF) and established the Joint Systems Program Office for this purpose. By 1982 system definition was completed, and in 1984 industrial competition commenced to produce prototype radars. As a result, production contracts were awarded to Unisys Corporation in 1988 and 1990. The major program objectives have been identified as: (1) weather monitoring and forecasting, (2) commercial and military flight operations, and (3) research into weather systems and climate. The nation has since been deploying radars throughout the U.S. (see Figure 6); the Puget Sound area radar was placed into service in February 1994 at Camano Island. Reliable data became available within around three to six months after radar installation. These were available for this project through an arrangement with the University of Washington's Department of Atmospheric Sciences, which acquires Level III NIDS radar data from WSI Corporation, Billerica, Massachusetts, one of several designated NWS WSR-88D data providers.

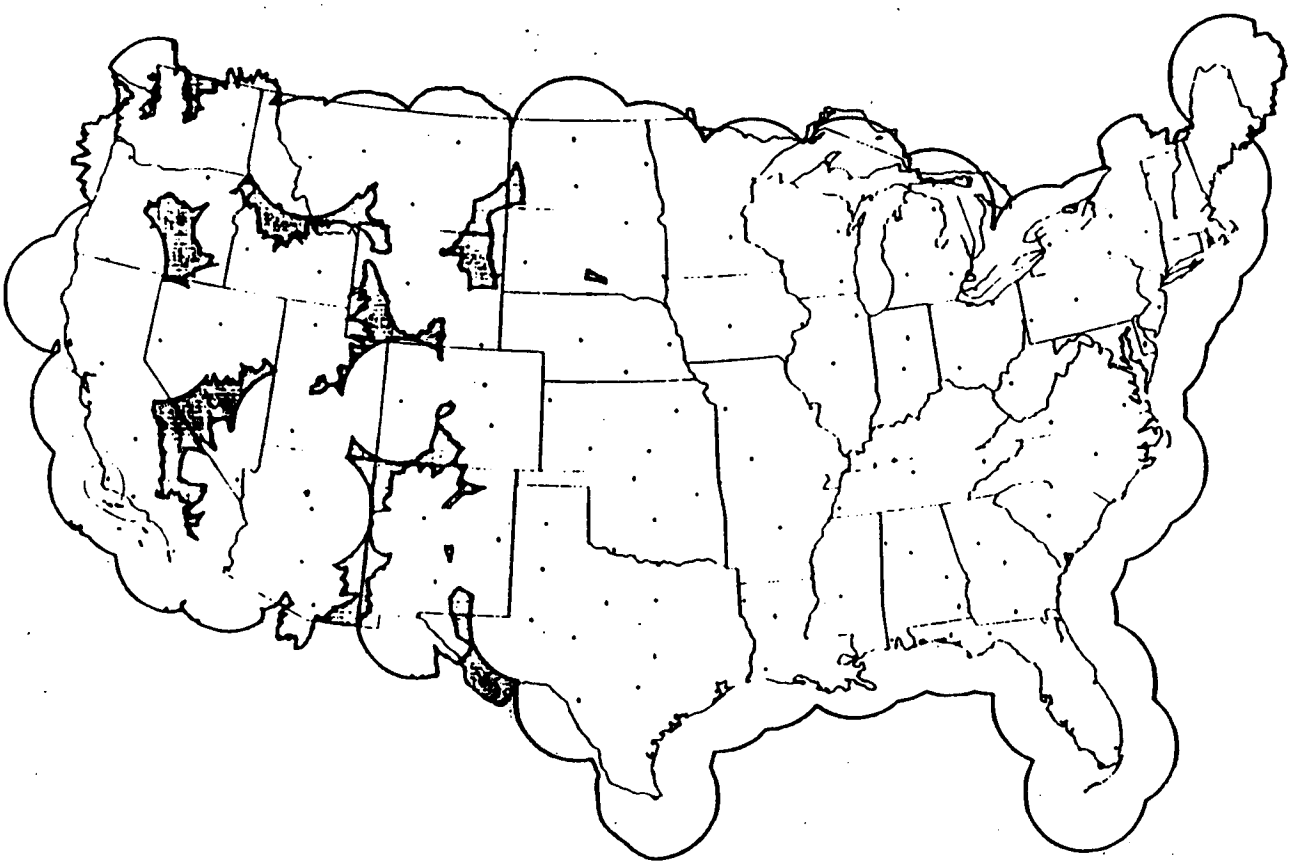

Figure 6. Depiction of the total coverage (at 10,000 feet elevation) provided by the completed national NEXRAD network.

These data have been made available to University users via the Department's World Wide Web Internet Site (http://www.atmos.washington.edu).

In addition to being available on-line, the Camano Island radar Level III data are archived for analysis of individual storms and for climatological and statistical investigations of weather and its impact on selected events such as traffic congestion, accident occurrence, and highway driving conditions.

System Characteristics

The WSR-88D radar operates at S-band wavelengths (10 cm) and has a maximum range of 230 km, although its most useful data are recorded within a range of around 100 to 150 km. The radar's primary observables are a reflectivity factor, which is a measure of scattered power; Doppler velocity, which gives the radial velocity of cloud and precipitation particles to and from the radar; and Doppler spread, or the standard deviation of radial velocity. The measurements are made over a large volume defined by a series of full azimuth scans at varying elevation angles ranging from 0.5° to 19°. Continuous scanning enables the volume scanned to be sampled by the radar at about 5-minute intervals during precipitation events.

FINDINGS

RADAR CHARACTERISTICS

The **NEXRAD** radar takes fine resolution measurements of reflectivity factor, mean radial velocity and velocity spectrum width; these data are then used to generate 39 categories of analysis products at cycle times ranging from 5 to 10 minutes (Klazura and Imy, 1993). Additional analysis products can be generated from the base data for special applications. This project focused initially on use of the base data and archived data sets. The latter are identified in Table 1, which indicates the products and associated specifications available on the **WSR-88D** system. Merging these data with geographical information on a given highway network and related traffic data will provide a basis for analyzing weather impacts on transportation system performance and will lead to improvements in the overall ground transportation management system.

Seattle WSR-88D Coverage

Areal Coverage

The Seattle area's NEXRAD radar coverage is illustrated in Figure 7. The radar is located on Camano Island. The figure shows that the extent of the radar's coverage depends both on the vertical height of coverage and on the radar's elevation angle scan, since topographic features (mountainous terrain) block the radar's beam from extending beyond the point of blockage. This general phenomenon is clearly indicated by the outside contours defined by the lower height bounds of the radar's coverage (depends on elevation angle and range) at each azimuth angle. Note that coverage is excellent throughout the entire residential Puget Sound area, whereas blockage is a major limiting factor both east and west where the Cascade and Olympic Mountains, respectively, limit propagation of the radar beams beyond the points of intersection of the beams with the topography.

Volume Coverage

Radar echoes are returned from volumes defined by the radar's antenna beam or radiation pattern transmitted wave-receiver/signal processing capabilities. The NEXRAD radar's antenna forms around a 1° circular beam pattern that diverges with range. Thus, for each elevation

Table 1. Standard analysis products and archived data sets of the NEXRAD WSR-88D radar system

VOLUME PRODUCTS	Spatial Resolution		Number of Data Levels Available	MAX Range of Product Computations (km)	Product Coverage (Dimensions)		Archived at NCDC (Level III)	NIDS Product
	km X	km or deg			Radius (km)	km X km		
Composite Reflectivity (CR)	1	1	8 and 16	230	230	—	—	—
	4	4	8 and 16	460	460	—	Yes	Yes
Composite Reflectivity Contour (CRC)	1	1	16	230	230	—	—	—
	4	4	16	460	460	—	—	—
Echo Tops (ET)	4	4	16	230	230	—	Yes	Yes
Echo Tops Contour (ETC)	4	4	16	230	230	—	—	—
Weak Echo Region (WER)	1	1	8	230	—	50 x 50	—	—
Layer Composite Reflectivity Average (LRA)	4	4	8	230 - 324	—	460 x 460	—	—
Layer Composite Reflectivity Maximum (LRM)	4	4	8	230 - 324	—	460 x 460	—	Yes
Layer Composite Turbulence Average (LTA)	4	4	8	150 - 213	—	300 x 300	—	—
Layer Composite Turbulence Maximum (LTM)	4	4	8	150 - 213	—	300 x 300	—	—
One Hour Precipitation (OHP)	2	2	16	230	230	—	Yes	Yes
Three Hour Precipitation (THP)	2	2	16	230	230	—	—	Yes
Storm Total Precipitation (STP)	2	2	16	230	230	—	Yes	Yes
One Hour Digital Precipitation Array (DPA)	Approx 4 (1/40 LFM)	Approx 4 (1/40 LFM)	100	230	230	—	Yes	Yes
Supplemental Precipitation Data (SPD)	Approx 40 (1/4 LFM)	Approx 40 (1/4 LFM)	8	230	—	13 x 13 of 1/4 LFM	Yes	—
Velocity Azimuth Display (VAD)	N/A	N/A	7	1 - 230	—	—	—	—
Velocity Azimuth Display Wind Profile (VWP)	N/A	N/A	5	1 - 230	—	—	Yes	Yes
Reflectivity Cross Section (RCS)	1	0.5	8 or 16	up to 230	—	—	—	—
Velocity Cross Section (VCS)	1	0.5	8 or 16	up to 230	—	—	—	—
Spectrum Width Cross Section (SCS)	1	0.5	8	up to 230	—	—	—	—
Vertically Integrated Liquid (VIL)	4	4	16	230	230	—	Yes	Yes
Severe Weather Probability (SWP)	28	28	N/A	230	230	—	Yes	—
Hail Index (HI)	N/A	N/A	5	230	230	—	Yes	—
Mesocyclone (M)	N/A	N/A	3	230	230	—	Yes	—
Tornadic Vortex Signature (TVS)	N/A	N/A	N/A	230	230	—	Yes	—
Storm Tracking Information (STI)	N/A	N/A	N/A	345	345	—	Yes	—
Storm Structure (SS)	N/A	N/A	N/A	345	345	—	Yes	—
Radar Coded Message (RCM)	Approx 10 (1/16 LFM)	Approx 10 (1/16 LFM)	9	460	460	—	Yes	—

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Table 1. (cont'd)

PRODUCTS AND ASSOCIATED SPECIFICATIONS AVAILABLE ON THE WSR-88D SYSTEMS

ELEVATION ANGLE PRODUCTS	Spatial Resolution		Number of Data Levels Available	MAX Range of Product Computations (km)	Product Coverage (Dimensions)		Archived at NCDC (Level III)	NIDS Product
	km X	km or deg			Radius (km)	km X km		
Base Reflectivity (R)	1	1°	8 and 16	230	230	—	Yes (0.5° TILT)	Yes (4 TILTS) 16 DATA LEV
	2	1°	8 and 16	460	460	—	—	—
	4	1°	8 and 16	460	460	—	—	—
Mean Radial Velocity (V)	0.25	1°	8 and 16	60	60	—	Yes (0.5° TILT)	—
	0.5	1°	8 and 16	115	115	—	—	—
	1	1°	8 and 16	230	230	—	Yes (0.5° TILT)	Yes (4 TILTS) 16 DATA LEV
Spectrum Width (SW)	0.25	1°	8	60	60	—	Yes (0.5° TILT)	—
	0.5	1°	8	115	115	—	—	—
	1	1°	8	230	230	—	Yes (0.5° TILT)	—
Storm-Relative Mean Radial Velocity Map (SRM)	1	1°	16	230	230	—	—	—
Storm Relative Mean Radial Velocity Region (SRR)	0.5	1°	16	230	—	50 x 50	—	—
Combined Shear (CS)	0.5	0.5	16	115 - 163	—	230 x 230	—	—
	1	1	16	115 - 163	—	230 x 230	—	—
	2	2	16	115 - 163	—	230 x 230	—	—
	4	4	16	115 - 163	—	230 x 230	—	—
Combined Shear Contour (CSC)	0.5	0.5	5	115 - 163	—	230 x 230	—	—
	1	1	5	115 - 163	—	230 x 230	—	—
	2	2	5	115 - 163	—	230 x 230	—	—
	4	4	5	115 - 163	—	230 x 230	—	—
Severe Weather Analysis (SWA)								
(SWR) Reflectivity	1	1°	16	230	—	50 x 50	—	—
(SWV) Velocity	0.25	1°	16	230	—	50 x 50	—	—
(SWW) Spectrum Width	0.25	1°	8	230	—	50 x 50	—	—
(SWS) Radial Shear	0.5	1°	16	230	—	50 x 50	—	—
Combined Moment (CM)								
Reflectivity	1	1°	8	230	—	25 x 25	—	—
Velocity	0.5	1°	N/A	230	—	25 x 25	—	—
Spectrum Width	0.5	1°	N/A	230	—	25 x 25	—	—

N/A means Not Applicable

(OVER)

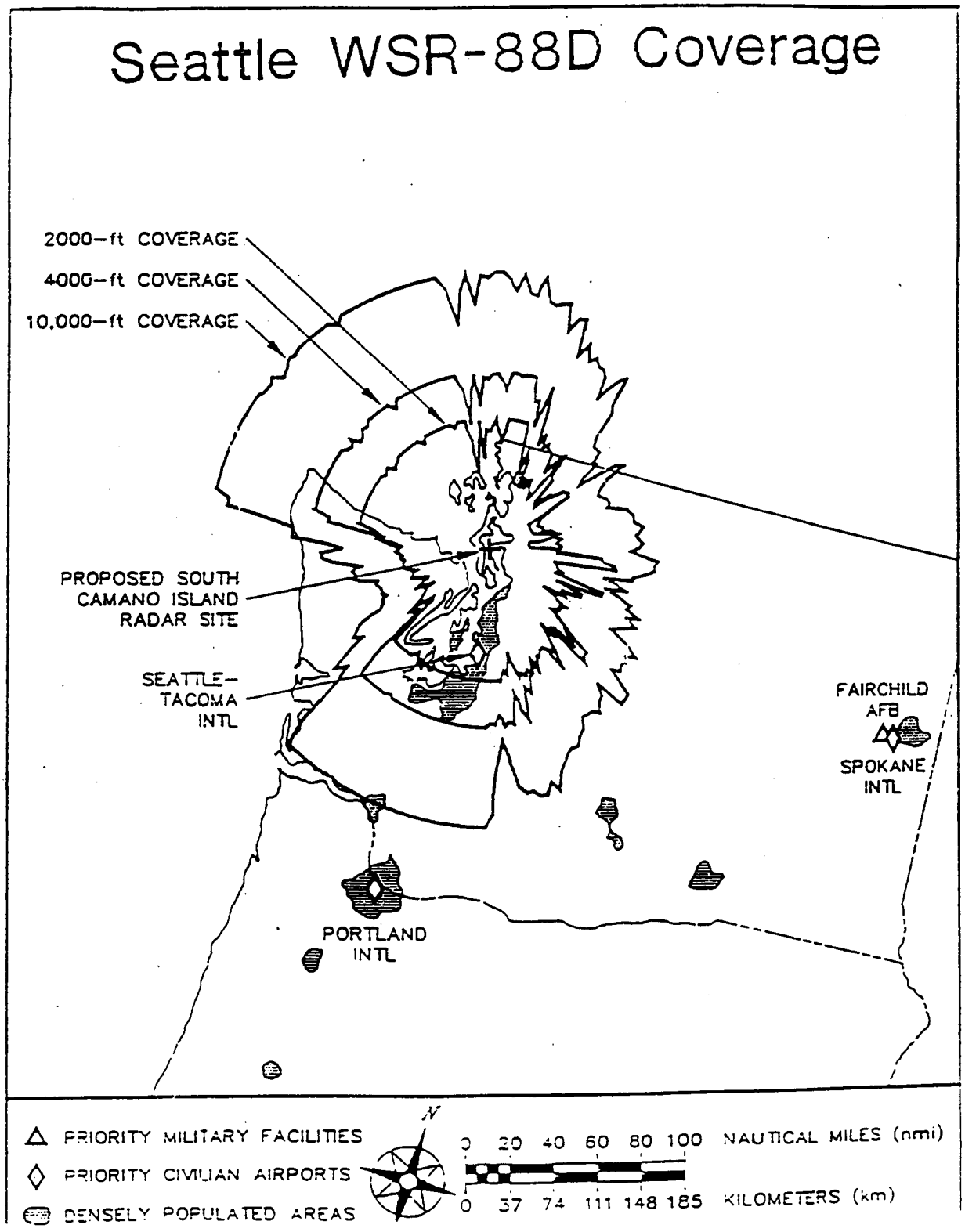

Figure 7. Seattle area WSR-88D NEXRAD area coverage.

angle scan, the scattering volume expands laterally with increasing range and covers different geographical sectors, as shown in Figure 7. This figure illustrates how, by consecutive elevation scans separated approximately by 1°, the radar can obtain information on meteorological events throughout a very large volume of possibly weather-containing atmosphere.

WSR-88D Products

A description of the computer algorithms used to generate radar-derived meteorological and hydrological products was obtained from the Operational Support Facility of the National Weather Service. Several of these were selected for review because of their possible relevance to traffic management problems. These products are examined later in this section with reference to possible traffic-related uses.

The National Weather Service has committed itself to providing unaltered NEXRAD Information Dissemination Service (NIDS) WSR-88D radar products to selected groups of subscribers cost free. This data source is derived from data gathered during radar scanning modes that cover atmospheric volumes extending from full azimuthal coverage at a prescribed series of elevation angles ranging from 0.5 to 19.5 degrees. A complete volume scan is repeated every 5 to 10 minutes, depending on weather conditions; during precipitation events the scan is set for 5 or 6 minutes, with the shorter period reserved for severe weather events. The data are readily accessible and constitute an excellent resource for application to this project and eventual implementation for highway traffic management and other related applications. A brief description of these products and an initial assessment of their possible utility for achieving the goals of this project are outlined below. Note that most of these products are given in formats that allow the data to be projected onto the geographical region covered by the radar out to a range of 124 nautical miles, or 230 km. They are usually displayed as intensity in false color on a computer screen and may be combined, altered via additional analytical algorithms and/or overlaid onto various maps or other graphics to aid understanding or relate to special applications.

Base Reflectivity (Four Lowest Elevation Angles)

Base Reflectivity, Reflectivity, or Reflectivity Factor Z is a measure of the power returned to the radar on a per unit volume basis when precipitation particles electromagnetically scatter the incident radar wave. It is strongly dependent on the type, size, and concentration of particles present in the scattering volume. However, when it is properly interpreted during rainfall, it can provide reasonable quantitative estimates of rainfall intensity. Under certain circumstances, it can also be used to discriminate between rainfall and snowfall regions of a storm and to estimate snowfall rates. This so-called base reflectivity is available at four elevation angles (0.5, 1.5, 2.5 and 3.4°). Reflectivity is usually measured on a logarithmic scale in dBZ values that range from around 10 to 55 dBZ at low elevation angles during detectable rainfall events; corresponding rainfall rates are about 0.1 mm h^{-1} (barely noticeable) to over 100 mm h^{-1} (very intense). NIDS Level III values of Z range from 0 and less to 75 dBZ in 5-dBZ intervals in precipitation mode at spatial intervals of 1 x 1 km pixels throughout the range of the radar.

These products provide clear evidence of the horizontal structure of storms and their evolution in time and space. Because the lowest elevation angle radar scan is nearest the ground, it is most closely associated with the actual rainfall reaching the ground. Therefore, it is considered the most useful of all the NIDS products for application to highway traffic management. Quantitative estimation of rainfall intensity may be derived from fairly well-established Z-R relationships where Z is in $mm^6\ m^{-3}$ ($10^{Z(dBZ)/10}$) and R is rainfall rate in millimeters per hour (mm h^{-1}); the relationship depends on empirical and experimental evidence that shows that Z and R are highly correlated with larger values of Z corresponding to higher values of R via a linear regression between the logarithms of Z and R. This relationship may be used to continuously monitor and forecast over short periods the precipitation history of weather events along designated highway routes or corridors. Measurements at higher elevation angles may also be useful for establishing the vertical extent and variability of a storm's structure or for viewing storms at long ranges when topographic blockage of the radar beam or escessive signal clutter interferes. Under certain meteorological conditions, these scans can also provide information about the presence and

location of the atmospheric melting layer, where ice phase precipitation particles melt into raindrops as they fall through the freezing level or height where the temperature is 0° C. This information may help identify elevations at which precipitation changes from rainfall to snowfall or mixed phase precipitation.

Composite Reflectivity

Composite reflectivity in dBZ is derived from the entire set of reflectivity data that constitutes a single volume scan. It is essentially the highest value of reflectivity *Z* that occurs over a given geographical location. Generally, it is less useful than reflectivity. However, when it is compared to the lowest elevation angle reflectivity, it indicates the vertical storm structure and may indicate either growth or decay of storm cells. When used in this manner, this product may prove useful for short-term (nowcasting (Browning, 1982)) forecasting of storms, an important application for traffic management.

Echo Tops

This product, like Composite Reflectivity, is derived from the entire volume scan. It is a display of the location and height (in 5,000-ft increments from 0 to 70,000 ft) of the highest altitude of 18-dBZ reflectivity values. It may be interpreted as the maximum height of significant precipitation. It may also be used to supplement base reflectivity, particularly in detecting conditions associated with anomalous propagation conditions that occur when unusual atmospheric vertical temperature profiles exist. Such events can result in significant reflectivities in the absence of concurrent significant precipitation. By itself, this product should not normally prove very useful for this project. However, when combined with other observations, it may provide useful information on storm intensity, hail detection, and nowcasting.

Vertical Integrated Liquid (VIL)

Vertical Integrated Liquid is derived from reflectivity measurements as a gross estimate of the vertical columnar amount of equivalent liquid water that occurs throughout the radar surveillance region. The product is divided into 16 levels, ranging from equal to or less than 0 to 70 kg m^{-2} in increments of 5 kg m^{-2}. This product is especially useful for detecting the possible

presence of large hail and the occurrence of severe weather, especially when combined with Base Reflectivity and Echo Top measurements. This parameter would not generally prove useful for this project except for severe weather. For example, it might indicate high surface winds and/or very intense, driving rains. However, considerable experience with actual events would be necessary to test these possibilities.

One-Hour Surface Rainfall Accumulation

This product is available following every scan and is derived from the reflectivity measurements; it is essentially an estimate of the one-hour running average of rainfall that occurs throughout the area covered by the radar. As indicated under Base Reflectivity above, it is derived from a relationship that equates reflectivity Z to rainfall rate R. Rainfall accumulation, ranging from 0 to 10 inches in 15 levels, over the last hour of the observations is available for display. The accuracy of this product can depend on several factors, including the height of the melting layer, the nature of the melting layer or type of precipitation particles present, climatic conditions such as time of year and type of storm, distance from the radar, and whether hail is present. One-Hour Surface Rainfall may be useful to this project, although separate estimates of rainfall accumulation from the Base Reflectivity data may prove more useful.

Three-Hour Surface Rainfall Accumulation

This product is similar to One-Hour Surface Rainfall Accumulation, except that it is available only after two hours of precipitation has fallen and accumulated. Outputs are updated every hour thereafter until precipitation stops for at least one hour. This product was designed to assist in flash flood prediction. Because of the relatively long duration between updates, other than indicating extended precipitation accumulation and being an independent reference for similar products that might be derived from the reflectivity data for use in this project, it would most likely be of little use for traffic management, except possibly for generic post-event analyses of weather-traffic relationships.

Storm Total Rainfall

This product is similar to the One- and Three-Hour Surface Rainfall Accumulation products. It provides estimates of the total rainfall accumulation over the radar's entire surveillance regime (124 n mi) as long as precipitation is observable above a given threshold anywhere in the coverage region. Like the other precipitation accumulation measures, it is updated after completion of every volume scan. Its projected use is primarily for assessing flash flood potential and watershed runoff. It may also be used for post-storm analyses and comparisons with rain gauge data. As currently structured, this algorithm is more climatological than weather-based and therefore would not generally be useful for application to this project. The resulting database, however, may prove very useful for ascertaining daily, weekly, and other climatologically significant measures of precipitation as future input to highway designers, or for relating this to the spatially dependent statistics of traffic and highway incidents.

Hourly Digital Rainfall Array

This product is essentially the same as the One-Hour Surface Rainfall Accumulation product, except that the units of rainfall accumulation are in dBA, which is indicated by 10 times the logarithm to the base 10 of the accumulation relative to 1 mm of accumulation; i.e., a rainfall of 100 mm would be represented by 20 dBA. This product conveniently scales and compresses a large range of possible accumulation (0.016 to 1,600 mm) into 1 range of -18 to +32 dBA. It is useful in that possible data are portrayed with good resolution over their entire range. Consequently, this product may prove more useful than One-Hour Surface Rainfall for this project; it may be of direct utility or for comparison with specially tailored products derived from the Base Reflectivity data.

Radial Velocity (Four Lowest Elevation Angles)

Radial Velocity is derived from the Doppler effect and, as such, is a measure of the mean radial velocity of precipitation or cloud particles in the radar scattering volume. It has many possible applications, foremost of which are to estimate environmental winds and to locate boundaries and regions of changing wind intensities and directions. The latter may be associated

with weather conditions that signify storm intensity, location, type, and stage of evolution. Data correspond to the data available in the Base Reflectivity product, i.e., they are at four elevation angles (0.5, 1.5, 2.5 and 3.4°) and range from -64 to +64 kts (-118.6 to +118.6 km h^{-1} or -32.9 to +32.9 m s^{-1}) in 15 levels. These data depend on the presence of precipitation particles or strong atmospheric variability in the absence of such particles and thus are only available in regions where Base Reflectivity values are detectable. These data may prove useful for this project as an indication and/or predictor of storm development, storm severity, storm forcing (e.g., frontal and wind shift boundaries often indicate cell development, and detection of convergence zone phenomena that regularly occur in the Puget Sound area can indicate the possibility of a prolonged storm in a given region), storm cell motion, surface winds, and storm relative motion.

Velocity Azimuth Display (VAD) Winds (Time vs. Height)

This product is derived from high elevation scan measurements of Doppler radial velocity. The velocity data are processed to produce time-height plots of average winds for the region surrounding the radar out to a distance of approximately 16 n mi (29.7 km) from the radar. The height to which winds may be found depends on the availability of radar echoes, whereas the product's representativeness depends on the complexity of the atmosphere near the radar, with non-uniform conditions indicating less reliability in the product's results. This product is most useful for meteorological forecasting and would in general not be useful for this project, although it can indicate potential storm severity or the stage of storm evolution, which may help in event nowcasting.

Layer Composite Reflectivity (Three Layers)

This product is similar to the Composite Reflectivity product; it is available after each volume scan and indicates the maximum reflectivity that occurs in three atmospheric layers, corresponding to the surface to 24,000 ft, 24,000 ft to 33,000 ft, and 33,000 to 60,000 ft. Data are given in seven levels, ranging from 5 to 75 dBZ. It may be used to detect the presence of anomalous propagation conditions and, in addition, may contribute to determining the stages of

storm evolution over the radar coverage area. This product may be useful for detecting and forecasting storm evolution and, as such, may be useful for this project.

RADAR DATA: SAMPLE OF BASIC IMAGE PRODUCTS

As indicated in previous sections, the most useful radar measurement for ground transportation applications is reflectivity factor Z. This observable indicates the power returned to the radar per unit volume from precipitation particles within that volume normalized to the transmitter power. Its intensity may be transformed into an estimate of rainfall rate through a so-called power law relationship

$$Z = a R^b \tag{1}$$

where Z is reflectivity factor in $mm^6\ m^{-3}$, R is rainfall rate in $mm\ h^{-1}$, and (a,b) are constant parameters that may vary according to climatic region, storm type, and/or areas within a storm. Typical values of (a,b) are (200, 1.6). Other values may range between (30 to 400 for a and 1.3 to 1.9 for b); the latter represent measurements over many climatic regions on the Earth and practically every type of storm possible (Battan, 1973). By using Equation 1, rainfall rates throughout the Puget Sound region and along specified highway corridors or routes can be estimated. These results will lead to assertions on storm intensities and wetness conditions, which may then be related to factors that affect driving and other highway operations.

The nature of reflectivity factor measurements is illustrated in Figure 8. This is an image of Z over the spatial domain covered by the Camano Island radar on April 21, 1994, soon after the radar was deployed. Each pixel or data point represents an average measurement over an area approximately 1x1 km^2 in size. The measurements are made at time intervals of around 5 minutes, long enough to capture a representative picture of the precipitation state over spatial scales of this magnitude. The circles signify intervals of 20-km distances from the radar. This particular image indicates two distinct storm events occurring in two regions of the Puget Sound area. A fairly intense cell is centered at around 90 km SSE from the radar, and a line of activity is seen along a

path extending SSW to NNE of the radar over a distance of approximately 140 km. The reflectivity factor values are indicated by the color coding of the data, with the most significant precipitation occurring at values of Z greater than around 20 dBZ. Continuous detection and tracking of such storm structures should be useful for appraising the effects of weather on traffic and should lead to improved means of its management. This project addressed this potential by comparing radar and rain gage measurements of rainfall rates to demonstrate radar's ability to monitor rainfall, and by manipulating and interpreting radar data for use in determining cause and effect relationships between weather, resultant driving conditions, impacts on traffic, and other highway operations. The data are also useful for post-factum weather-related accident investigation.

An auxiliary data set of possible additional utility for this project is illustrated in Figure 9. This shows Doppler velocity, which is a measure of the mean radial velocity of the precipitation particles in the scattering volume. It illustrates, to a limited extent, the general motion of storms and the atmospheric dynamics involved in storm development and evolution. In this region, it has particular utility for relating storm behavior to orographic forcing and the convergence zone phenomenon. The latter is associated with westerly and southwesterly flows and their interactions with the Olympic Mountains. In contrast to most other storm systems, these storms often dwell for extended periods in certain regions of the Sound. Their detection is therefore of special relevance, in that they may result in extended periods of poor driving conditions (e.g., very wet roadways and poor visibility) and, when they occur near the Cascade Mountains, may produce significant amounts of snowfall near the passes, requiring the special attention of highway maintenance personnel.

POTENTIAL BENEFITS TO HIGHWAY TRAFFIC MANAGEMENT

The previous sections demonstrate that the reliable, continuous availability of the NEXRAD WSR-88D radar data provides a new weather surveillance resource of great potential value for

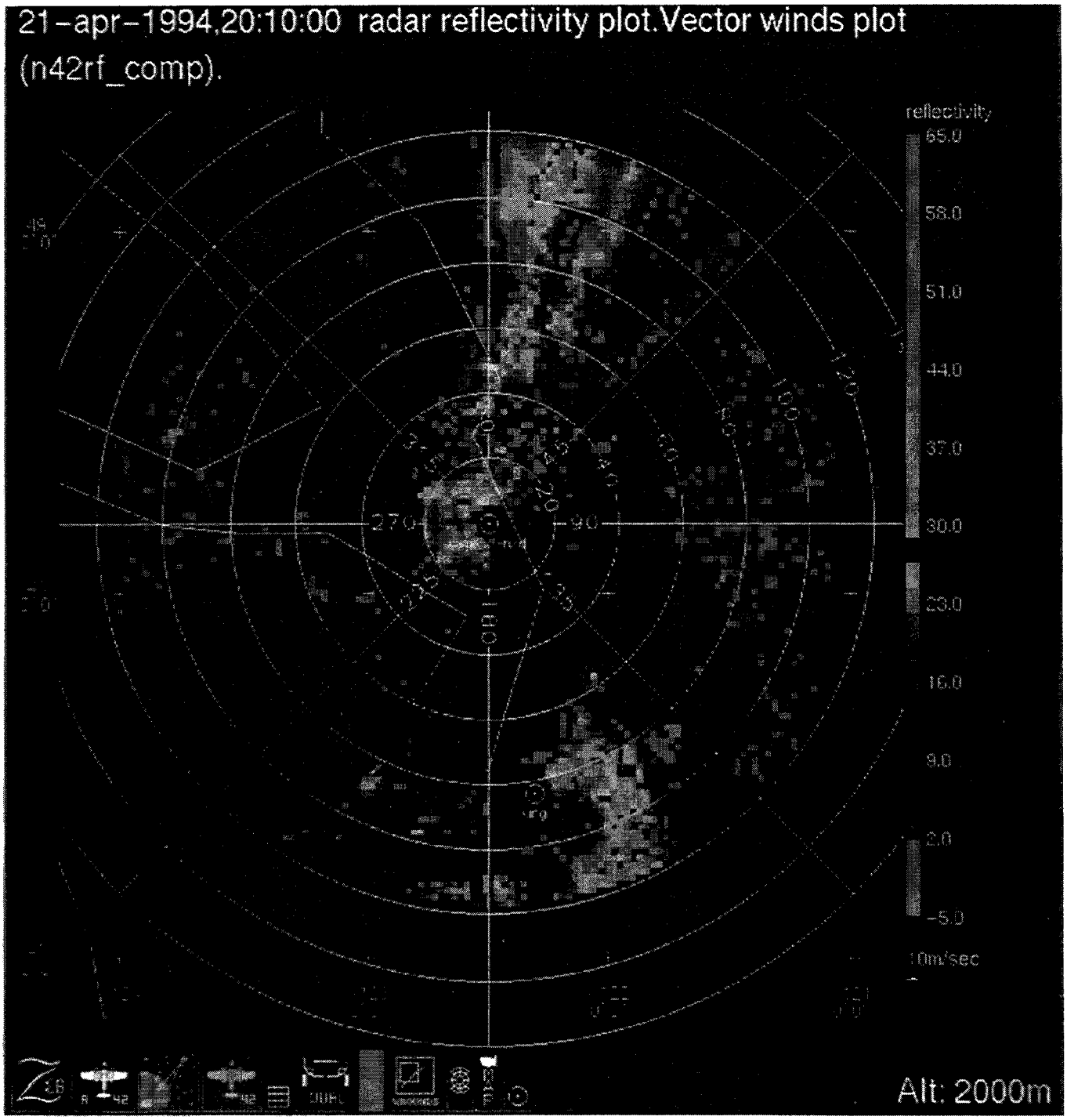

Figure 8. Radar reflectivity factor in the Puget Sound Region, April 21, 1994.

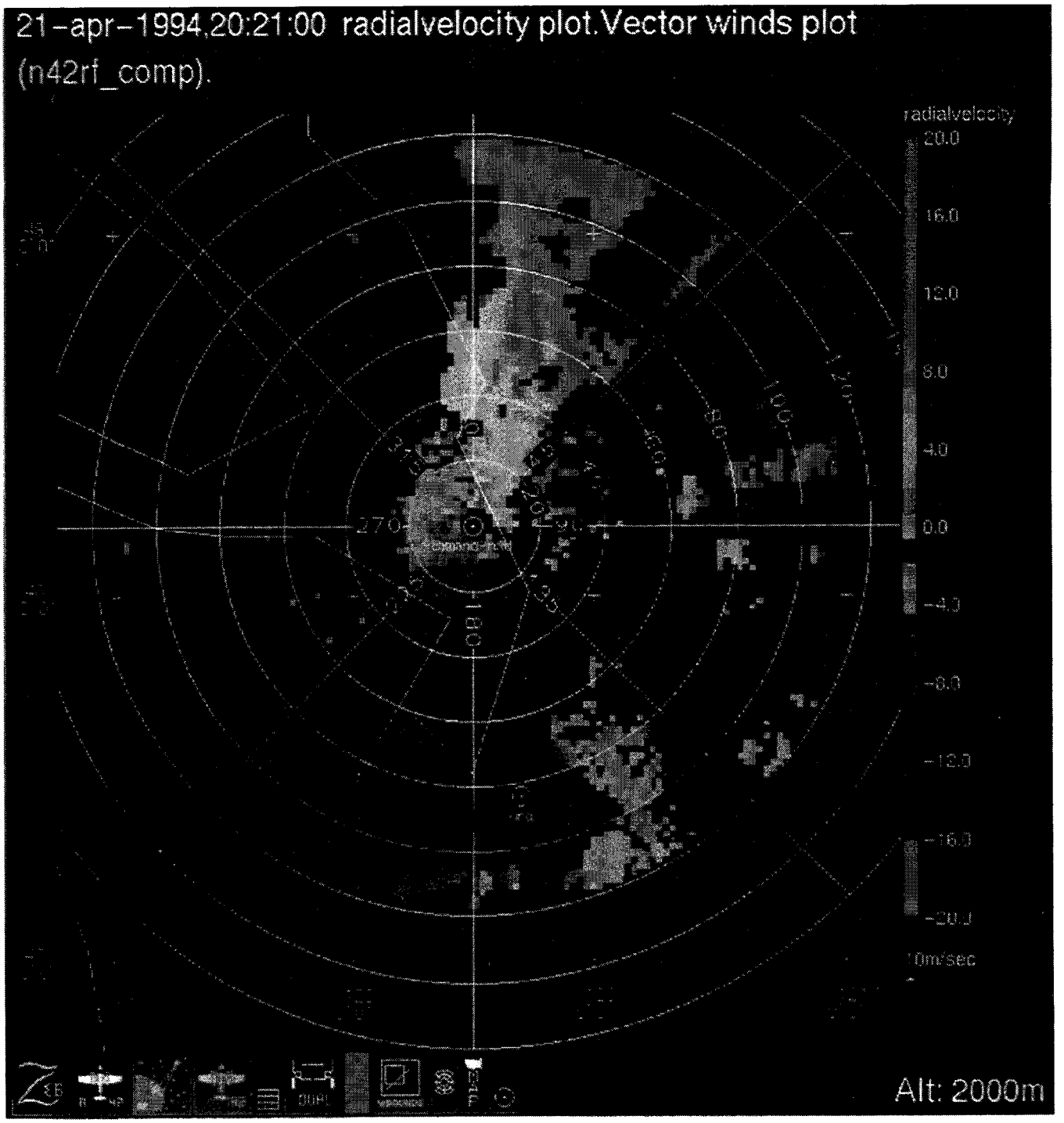

Figure 9. Radar Doppler velocity in the Puget Sound Region, April 21, 1994.

improving traffic management and related operations. This data source has similar potential for the extensive ferry operations in the region. A summary of these benefits include the following:

- accumulation of an archive of high quality weather data, relevant to ground transportation needs
- improved understanding of weather-traffic relationships
- improved methods of dealing with adverse weather in highway operations
- more effective traffic management systems
- reductions in weather-related accidents and adverse commercial impacts
- better preparedness of public service providers such as police, fire fighter and health emergency agencies to deal with adverse weather
- greater public awareness and understanding of weather and its effects on traffic and safety.

We now take a look at how the NEXRAD radar products can be used to estimate highway conditions due to weather phenomena.

Application I

Two of the most important safety issues in traffic management are wet-pavement conditions and visibility, both of which are related to rainfall (OECD, 1976). The former is demonstrated by a National Transportation Safety Board study that showed that fatal traffic accidents are approximately 3.5 times more likely to occur when pavement is wet (Dahir and Gramling, 1990). Therefore, the ability to collect real-time information about the most common weather phenomenon that influences pavement traction and driver visibility, namely rainfall intensity, is of major significance to the field of ground transportation. In particular, NEXRAD radar estimates of rainfall rate can be interpreted in terms of highway wetness and visibility, and this information can then be used to analyze highway operations and be applied to traffic management. This study demonstrated the validity of these relationships by introducing and using a Highway Wetness Index (HWI) and a Visibility Impairment Index (VII). This material is taken in part from Seliga and Wilson (1995) and Seliga and Ngugen (1996).

Methodology

The NEXRAD Information Data Service (NIDS) products include a radar reflectivity factor at approximately 5-minute intervals with a spatial resolution of 1 km² (Baer, 1991; Klazura and Imy, 1993). This radar reflectivity, with appropriate spatial averaging, can be converted to rainfall rates using a standard Z-R relationship, such as the one corresponding to the Marshall and Palmer (1948) drop size distribution. Using a geographical information system approach, rainfall rate maps can be combined with highway route maps to obtain precipitation estimates for any location along a specified highway route. This information can then be used to determine the sections of highway where rainfall intensity is high and, thus, where road conditions are hazardous because of wetness and reduced driver visibility. The data processing used to extract this information is illustrated in Figure 10.

Highway Wetness Index (HWI)

A highway-wetness index (HWI) can be defined by utilizing a simple first-order relaxation model of the degree of wetness, W, with rainfall intensity, R, as input, along with a pavement drying factor to account for runoff, evaporation, and forced drying due to traffic volume. This model may be expressed as

$$dW/dt + \beta W = \alpha R \tag{2}$$

where α is a constant that describes the dependence of W on rainfall rate, R, and β is the relaxation constant of the pavement drying process. Both (α, β) will depend on conditions such as pavement type, climate, and traffic conditions, but both are expected to remain relatively constant at any given time of day. Eventually, representative values will be required; these are expected to be established through experimentation and standardization. A more appropriate measure of this index will allow for the large range of variation that results from the natural variability of rainfall rate (e.g., ranging from around 0.1 to over 100 mm-h^{-1}). In accordance with similar measures in

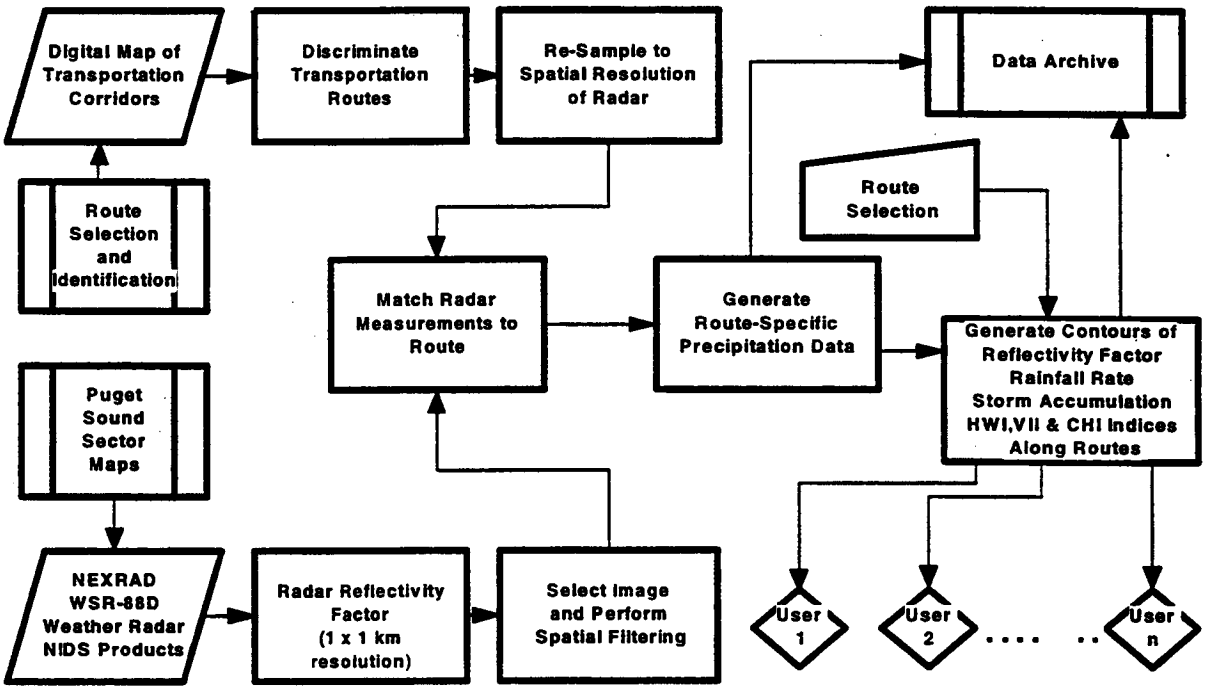

Figure 10. Data processing scheme for transforming NEXRAD radar data into rainfall-dependent parameters for ground transportation applications.

science and engineering, this index may be defined in terms of decibels relative to a standard measure; in this case, an appropriate index is

$$\mathrm{HWI} = 10 \log (W/W_r) \qquad dB\_HWI \tag{3}$$

where W_r is the relative wetness parameter. A value of $W_r \approx 0.125$ is a reasonable first estimate of the minimum value of this parameter at which roadway conditions begin to be influenced. The estimate of W_r is determined from its steady state value,

$$W_s = \alpha \beta^{-1} R \tag{4}$$

with $\alpha = 25$ mm^{-1} and $\beta = 5$ h^{-1}. This value of W_r is 0.1 times the value of W that a steady state rainfall rate of 0.25 mm-h^{-1} would produce under the same circumstances. It was selected here as a reference because this amount of rainfall over an hour's time is expected to reduce friction by as much as 75 percent of its dry value. The parameter b was chosen so that the average time for W to reach 0.1 of its initial value is around 30 minutes, a typical pavement drying time (Harwood et al., 1987).

With proper testing and calibration, the index HWI should denote both the degree of wetness and possibly when and where water has a high likelihood of being deep enough to cause hydroplaning and total loss of vehicle traction. This information would allow traffic managers to identify portions of a highway where wetness was apt to seriously reduce traction and to determine where water depth might have surpassed a critical threshold, possibly resulting in hydroplaning and serious deterioration in driving conditions.

An example of HWI is shown in Figure 11, which is a contour plot of this index as a function of time and distance along the I-5 corridor from Tacoma to Marysville; Seattle is nearly equidistant from both endpoints. The plot clearly shows the degree, times, and places along this major artery where wetness is a factor for the driving public. The temporal persistence in roadway

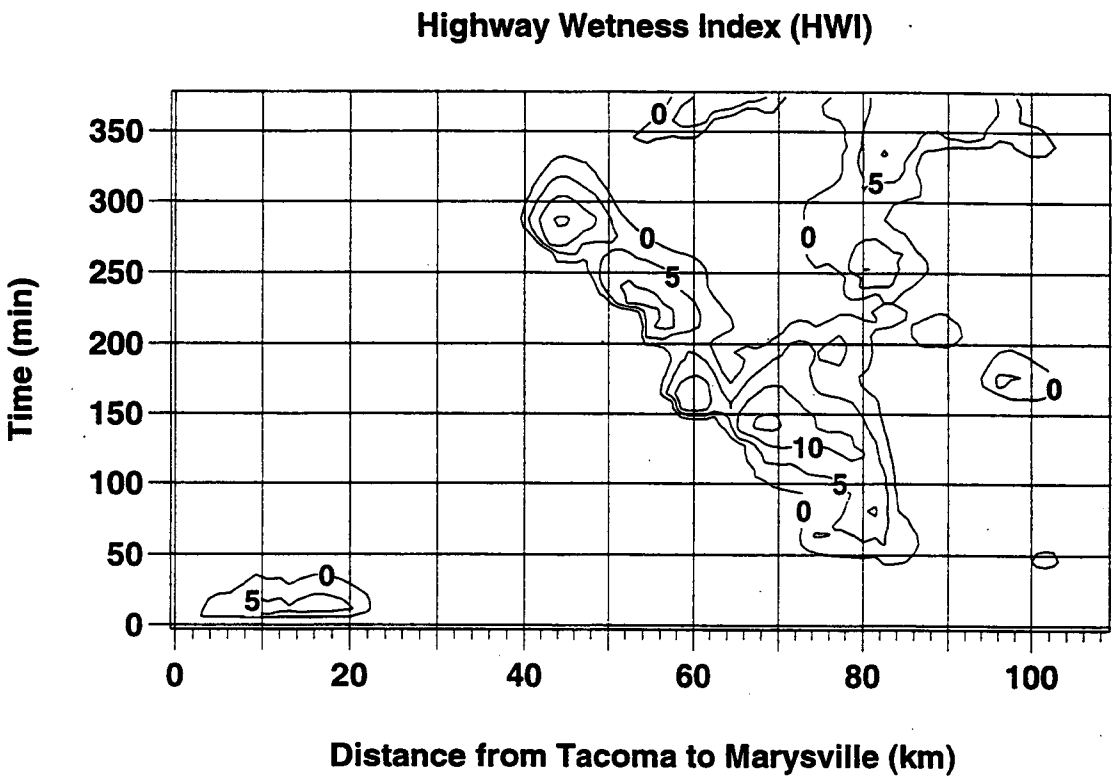

Figure 11. Highway Wetness Index in *db_HWI* derived from NEXRAD radar data (13 April 1995: 0 min = 1908 UT =1108 PST). Contours are in 5 dB steps beginning with 0 dB.

wetness is also evident as time trails in the contours, following the passage of a number of storm cells.

Visibility Impairment Index (VII)

The second most important factor in normal highway driving is visibility, which is also affected by rainfall. A reasonable assumption here is that the ability to see an object while driving is dependent on the optical extinction, κ, associated with rainfall. That is, visibility, V, relative to a non-rainfall condition, should deteriorate according to an exponential law:

$$V = V_o \, e^{-\kappa d} \tag{5}$$

where Vo is the non-rainfall visibility, κ is the optical extinction coefficient in Nepers-m^{-1}, and d is a reference distance for highway driving (taken here to be 50 m). As with highway wetness, visibility would be better measured as a visibility impairment index that increases with decreasing visibility. It should also allow for large variability in visibility associated with large variations in rainfall intensities that occur naturally. Thus, a reasonable measure of relative visibility loss or impairment is given by

$$\mathrm{VII} = -\,10 \log (V/Vo) \quad dB\_VII \tag{6}$$

$$\mathrm{VII} = -\,4.34\, \kappa d = 217\, \kappa \qquad dB\_VII \tag{7}$$

where VII is the Visibility Impairment Index in dB_VII, and d = 50 m is used as a reference distance for visibility. Optical extinction, κ, may be related to rainfall rate, R, through a power-law relationship (Ulbrich and Atlas, 1978),

$$\kappa = 1.6\, R^{0.62} \qquad Nepers\text{-}km^{-1} \tag{8}$$

This results in

$$\mathrm{VII} = 0.35\, R^{0.62} \qquad dB\_VII \tag{9}$$

This radar-derived index can then be used to assess the effects of rainfall on driver visibility, subject to evaluation and testing under actual conditions. The visibility index VII, corresponding to Figure 11, is shown in Figure 12. It is also noted that visibility impairment is much more complex than indicated here, involving other factors that are not considered. For example, splash, vehicle speed, glare, and wiper response are important factors that should eventually be included in VII.

Application of Indices

The results shown in figures 11 and 12 may be used separately or together as a Combined Hazards Index (CHI_dB) by simple linear combination of HWI and VII, as shown in Figure 13. Real-time contour or false color images of all of these NEXRAD-derived parameters are expected to be of great value to urban highway operations managers, and an invaluable tool for studying traffic-weather relationships. For example, in Seattle, the Traffic Systems Management Center (TSMC) will be able to use these data and related nowcasts to inform public sector service providers of roadway conditions and to modulate traffic flow to optimize volume and avoid accidents. In addition, speed, occupancy, and volume contours can be compared and correlated with the indices introduced here, leading to both general and highway-specific identification of weather related transportation events.

Application II

Traffic Behavior

The WSDOT TSMC operates an inductance loop system that detects volume and occupancy along a major portion of the I-5 corridor that lies within the Tacoma to Marysville corridor, the area used to illustrate the indices HWI, VII, and CHI (figures 11, 12, and 13, respectively). These data

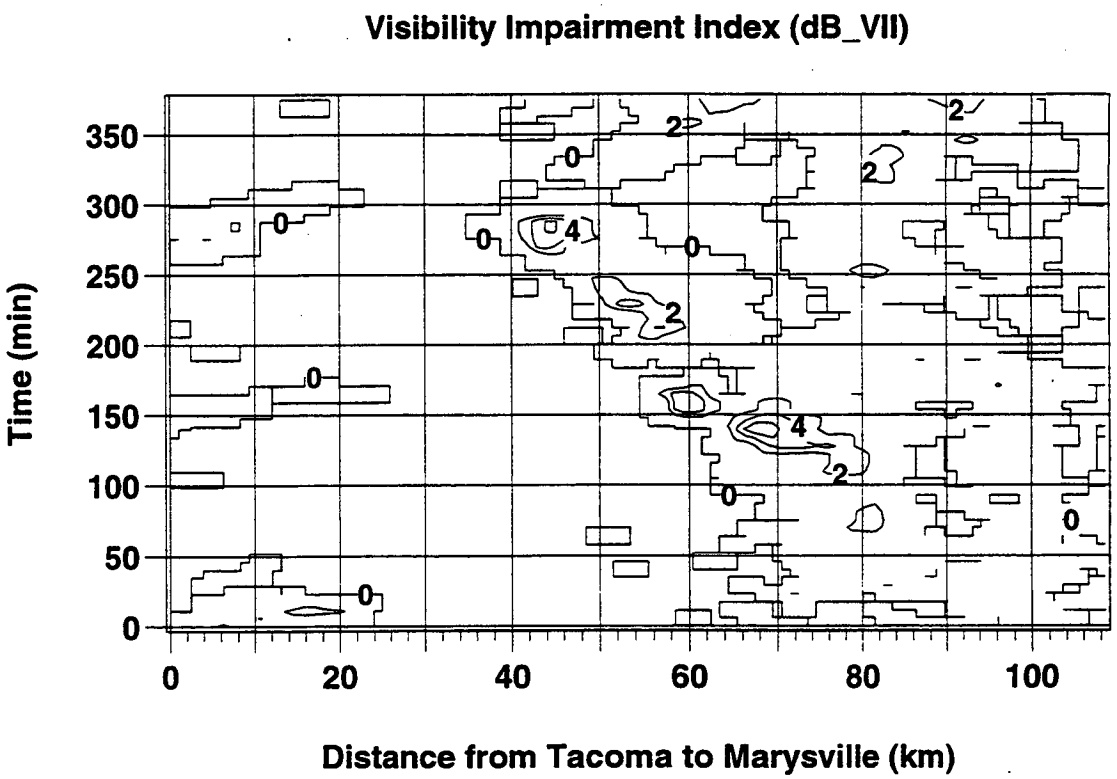

Figure 12. Visibility Impairment Index in *db_VII* derived from NEXRAD radar data (13 April 1995: 0 min = 1908 UT = 1108 PST). Contours are in 2-dB increments beginning with 0+ dB. Note that the 0 dB contour identifies the radar-detectable occurrence of very light rainfall.

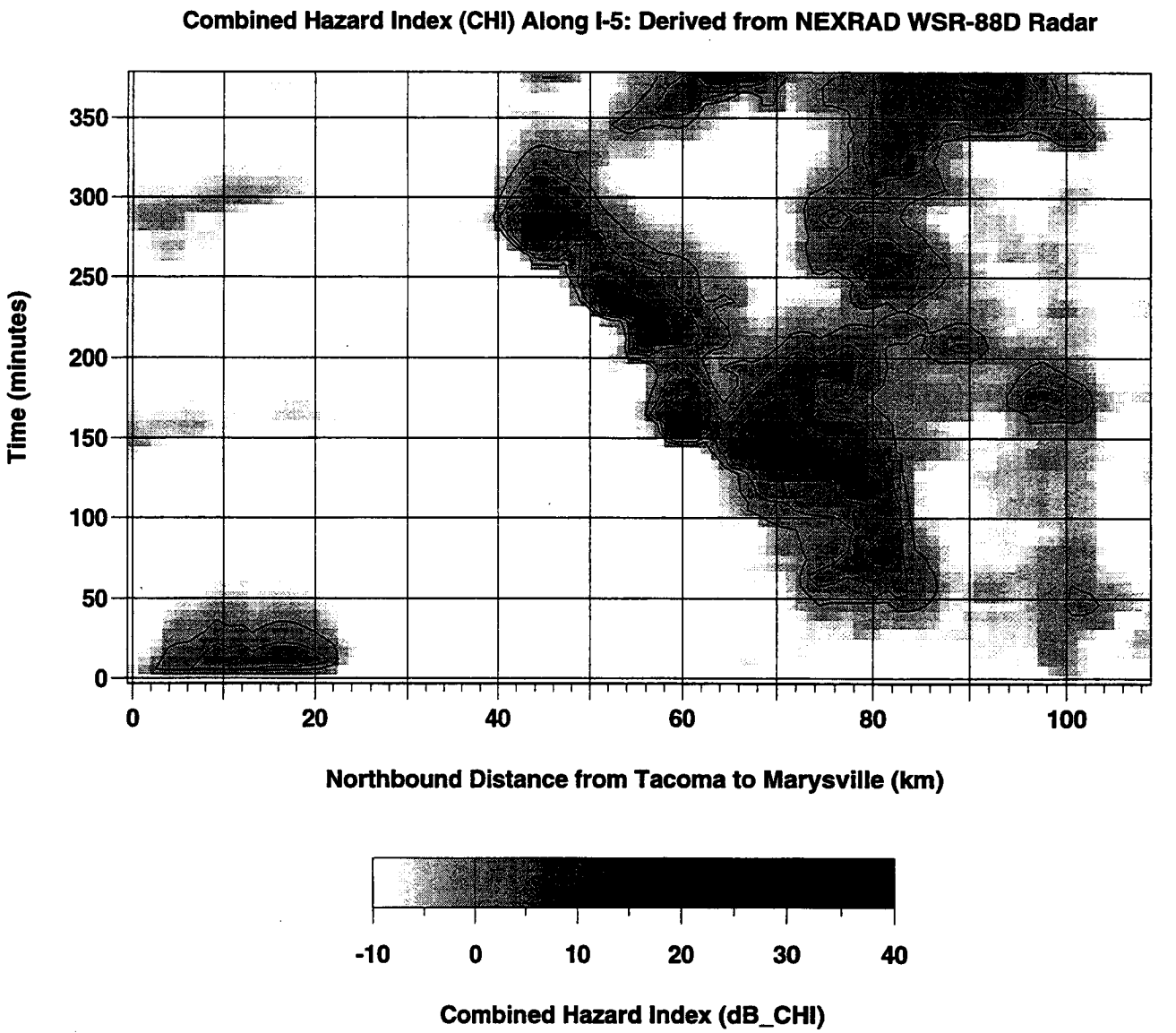

Figure 13. Combined Hazard Index in *db_CHI* based on equal weights for HWI and VII of figures 11 and 12, respectively. Contours are in 5-dB increments beginning with 0 dB.

are used in conjunction with analysis of the traffic indices to examine the combination of the traffic indices and actual traffic data. This work is taken from Seliga and Nguyen (1996).

Data from this system provide an excellent basis for evaluating the relevancy and possible importance of the radar-based highway condition parameters or indices to ground transportation. Accordingly, 5-minute occupancy and volume data from the inductance loop system were used to derive normalized speed and acceleration parameter contours for the same time period. Speeds normalized to station average speeds were used in order to reduce artifacts caused by outages of individual lane detectors; such occurrences would necessarily alter the proportionality constant k_s of the speed-volume-occupancy relationship

$$S = k_s \frac{Vol}{Occ} \tag{10}$$

where (S, Vol, Occ) are speed, volume, and occupancy of the traffic flow. Normalization of S at each station is obtained from

$$S_n = \frac{S}{\bar{S}} \tag{11}$$

where the overbar is the time-averaged value of S for that station. A second motion-based acceleration parameter, A_n, was derived from S_n via differentiation

$$A_n = \frac{\partial S_n}{\partial t} \tag{12}$$

where t is time and the location is held constant. Contour plots of northbound (S_n, A_n) for the same date and time period displayed in figures 11 through 13 are given in figures 14 and 15, respectively.

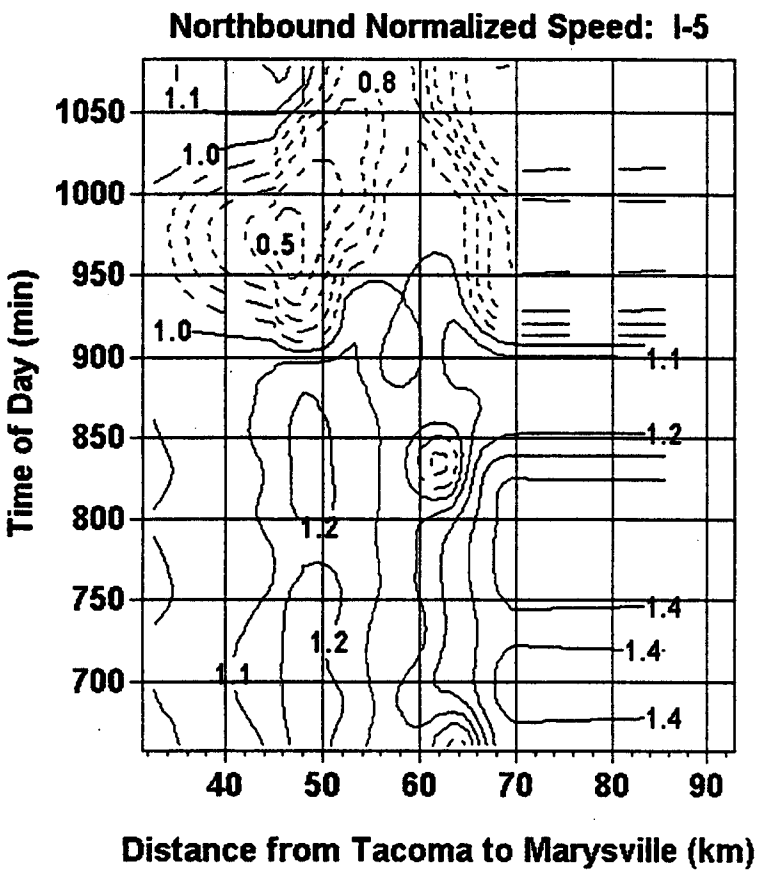

Figure 14. Northbound normalized speed along I-5, corresponding approximately to the HWI, VII, and CHI indices given in figures 11–13, respectively (13 April 1995: 660 min = 1900 UT = 1000 PST).

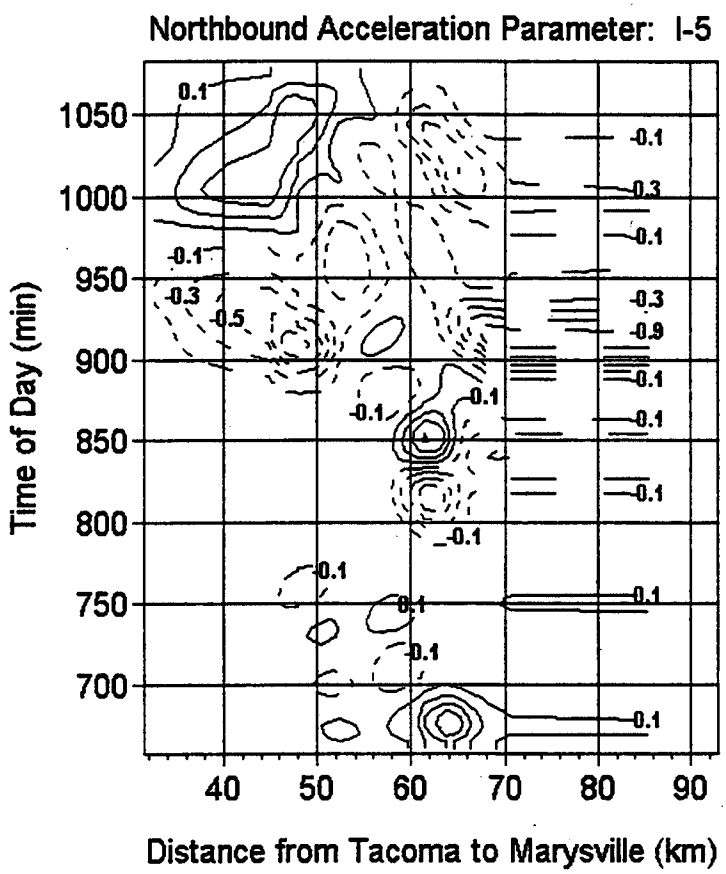

Figure 15. Northbound acceleration parameter along I-5, corresponding approximately to the HWI, VII, and CHI indices given in figures 11–13, respectively (13 April 1995: 660 min = 1900 UT = 1100 PST).

Rainfall-Traffic Relationships

To compare the results of the previous sections, care had to be exercised to account for time differences in the plots. The radar-derived plots start at 1108 PST (0 min. in figures 11 through 13), whereas the traffic data begin at 1100 PST (660 min. in figures 14 and 15). Because the radar values are measured about 5 minutes before the rain reaches the ground and the traffic data cover the 5-minute period following the time mark (therefore centered in time at 2.5 minutes after the record), there is an approximate 10-minute difference between the initiation of the radar and that of the traffic contours. That is, to achieve optimum comparisons, the traffic data must beshifted backward 10 minutes for best examination of the relationships between radar-based indices and traffic patterns. Thus, comparison of figures 14 and 15 with 11 through 13 should be done with this adjustment. Figure 16 is an overlay of the NB contoured acceleration parameter and a gray scale image of CHI, that accounts for these time differences. The response of traffic to the rainfall event are evaluated below through reference to this figure.

The results show that the first significant feature of the storm began crossing the path of I-5 at a distance of 72 to 85 km at around t=50 min. and shortly thereafter produced a CHI of 5 *db_CHI*. An intensity of 10 *db_CHI* was reached at around 80 km and lasted for about 25 minutes. This location is sparsely monitored by the inductance loop system, so a clear response of the traffic to this cell is not evident in A_n. As time progressed, the storm intensified and traveled southward, centered at 68 km, 140 min., and reaching a peak value of CHI greater than 20 *db_CHI*. A significant traffic reaction is now evident in the A_n parameter. Negative values of A_n, down to less than -0.7, indicate an apparently strong traffic reaction to the storm. A second cell of somewhat less intensity (less than 20 *db_CHI*) occurred shortly afterwards, centered at 60 km, 160 min; much of the deceleration associated previously with the more intense cell also appears related to this cell. When this cell's intensity became less than around 10 *db_CHI*, the traffic began a recovery phase, seen from the increasing acceleration pattern that followed the earlier deceleration pattern; this acceleration reached a maximum A_n of 0.7 at 62 km, 190 min. The storm

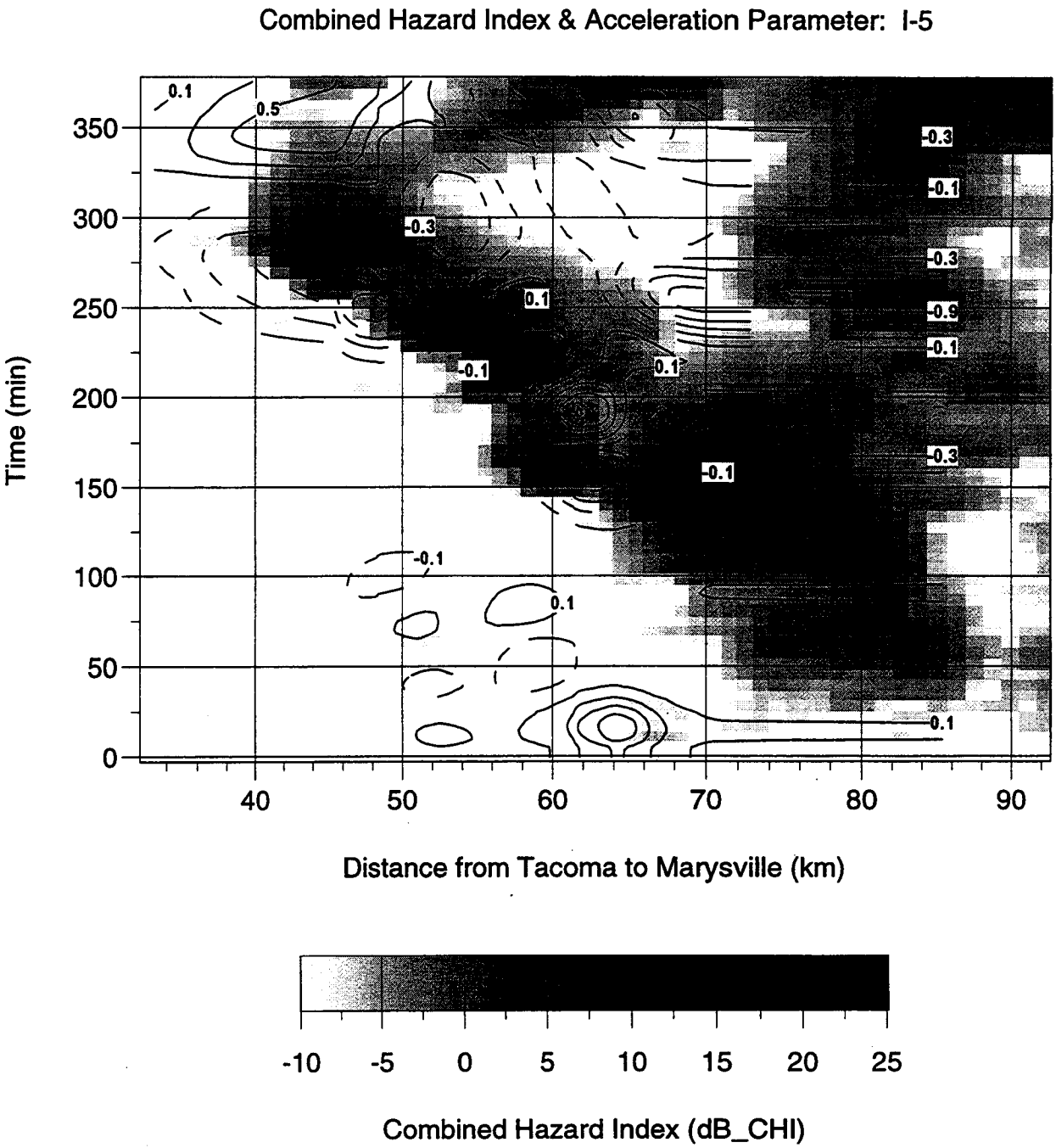

Figure 16. Time-concurrent overlays of radar-derived *db_CHI* and an I-5 acceleration parameter for the event of April 13, 1995.

then continued to drift farther southward and reintensified, reaching another peak of around 15 *db_CHI* at 54 km, 230 min. Once more, the traffic reacted by decelerating along the highway and over time. In this instance, however, another, more intense cell occurred, centered at 45 km, 280 min. This cell seems to have influenced the traffic flow further by extending the deceleration over much larger spatial and temporal domains than the first cell. That is, this portion of the storm, although exhibiting comparable values of *db_CHI* to the one at 68 km, 140 min, seems to have had a much greater effect on traffic flow. Using the contours of A_n as a gauge of this influence, one might infer that this portion of the storm's impact on traffic was greater than the earlier phase by more than a factor of two in both space and time. Clearly, such significant differences are most likely related to the location of the cells and the time of day, as well as CHI and possible weather- or other-induced accident/events. The first interaction of the storm system with I-5 occurred well north of Seattle shortly after noon, whereas the last portion of the system occurred in the city of Seattle at the beginning phase of the evening rush hours (post 3 p.m. local time).

The above analysis presents strong evidence of how rainfall, with its effects on highway wetness and driver visibility, can influence traffic flow. It also shows that the NEXRAD radar system offers an advantageous means of studying these effects while providing transportation managers and others with valuable information on freeway driving conditions. Contoured plots and/or intensity-modulated images of the HWI, VII, and CHI indices can be combined with traffic information in real time, not only to relate weather events to traffic behavior but also, with experience, to predict highway conditions via statistical inference. Among other things, this should lead to the development and implementation of strategies that reduce congestion, enhance safety, and improve highway design.

Case Study I

One of the other considerations in developing the highway indices was the reliability of the NEXRAD radar-derived rainfall rate estimates. If rainfall rate estimates were not reliable, it would be difficult to develop fully reliable indices of weather-related highway conditions. The first case study examined this concern.

The estimation of rainfall rates for July 9, 1995, was examined by using the NEXRAD radar reflectivity measurements and the Marshall-Palmer relationship, as previously described. The results from this case study are in Seliga and Nguyen (1996) and Seliga and Chen (1996). Because a rain gage provides the most direct way to measure rainfall rate on the ground, it can be used as a reference to evaluate the accuracy of the radar-estimated rainfall rates. For this study, two recording rain gages were used: one located on the top of the Electrical Engineering Building at the University of Washington in Seattle and another at Edmonds, Washington. The distances with respect to the NEXRAD radar at Camano Island are 61.6 and 43.2 km, respectively.

Each of the radar estimates were adjusted in time for optimum correlation to account for time differences associated with the fall time of the raindrops, the radar's spatially based measurements, and the gage's time-based measurements. Figure 17 shows the comparison between rain gage- and radar-derived rainfall rates and accumulations for the University of Washington site. Figure 18 shows the comparison between rain gage- and radar-derived rainfall rates and accumulations for the Edmonds site. For this event, the comparisons were quite good.

The rainfall rate estimates were improved by determining the storm's movement. Storm motion is estimated to determine a swath of measurements that approximate the corresponding temporal average rainfall rate at a given ground location. This approach has been previously used successfully in comparisons between ground-based rainfall measurements and inferences from radar polarimetric-based measurements (Aydin et al., 1990). When the rainfall rate measured by the rain gage is compared with that obtained from the radar reflectivity measurements, the time shift due to raindrop fall time must be considered. This is dependent upon drop terminal velocity, which is influenced by drop size. Because this information was not available, a time shift of 5 minutes was assumed.

Figure 19 shows the comparison of rainfall rates, and Figure 20 shows the accumulations for the University gage. Note that swath smoothing is evident, which results in a better correspondence to ground truth, as seen by the gage. This method shows promise and needs further investigation for other storm events.

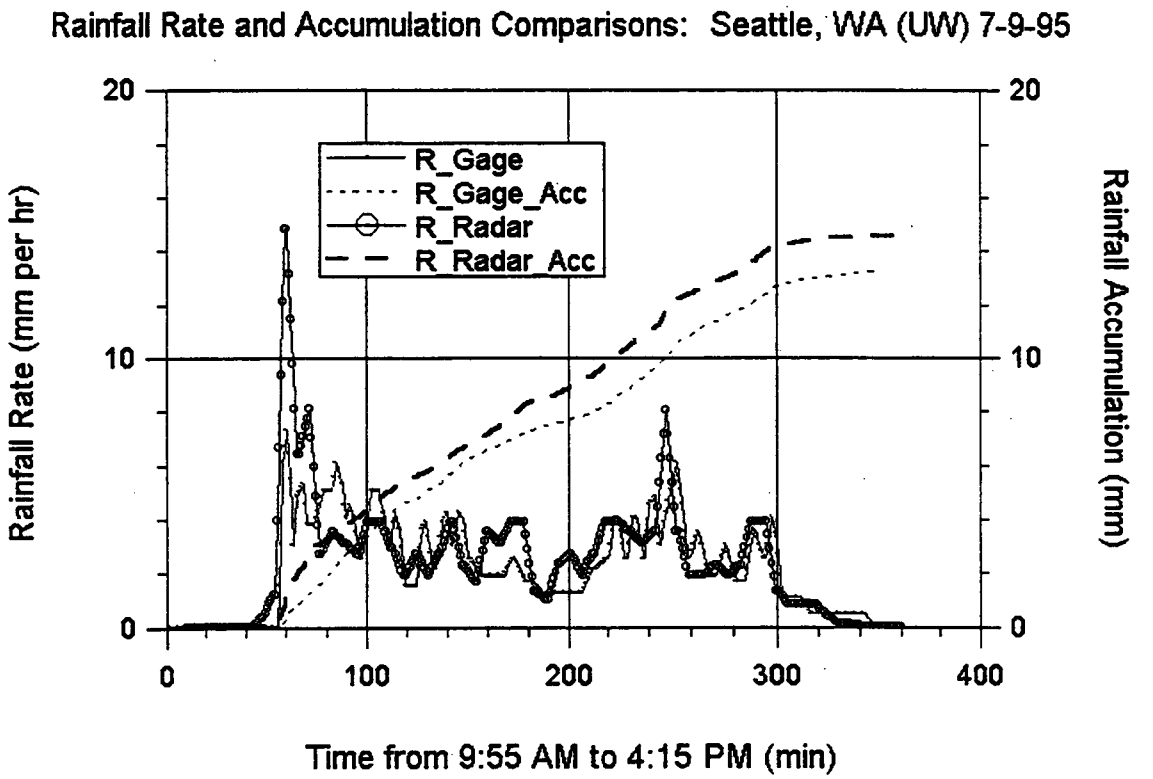

Figure 17. Comparison of rainfall rates and accumulations obtained from the NEXRAD WSR-88D radar and a rain gage located at the University of Washington on July 9, 1995.

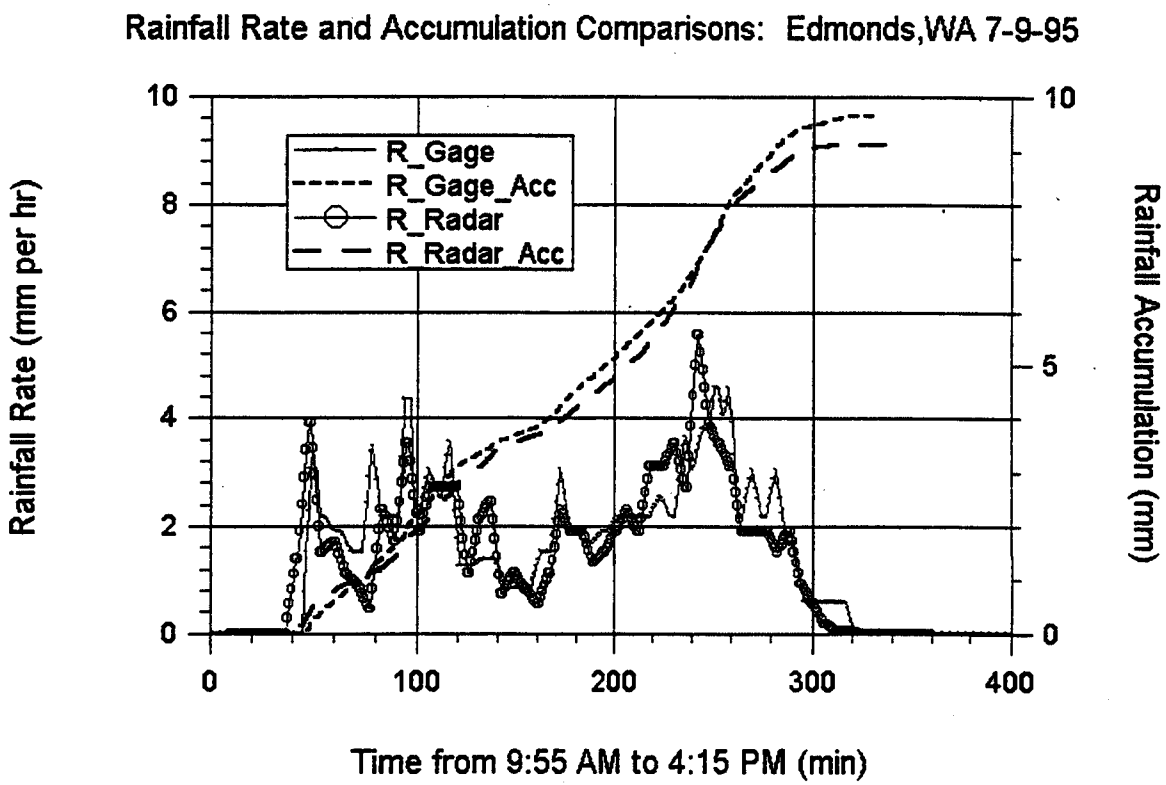

Figure 18. Comparison of rainfall rates and accumulations obtained from the NEXRAD WSR-88D radar and a rain gage located at Edmonds, Washington on July 9, 1995.

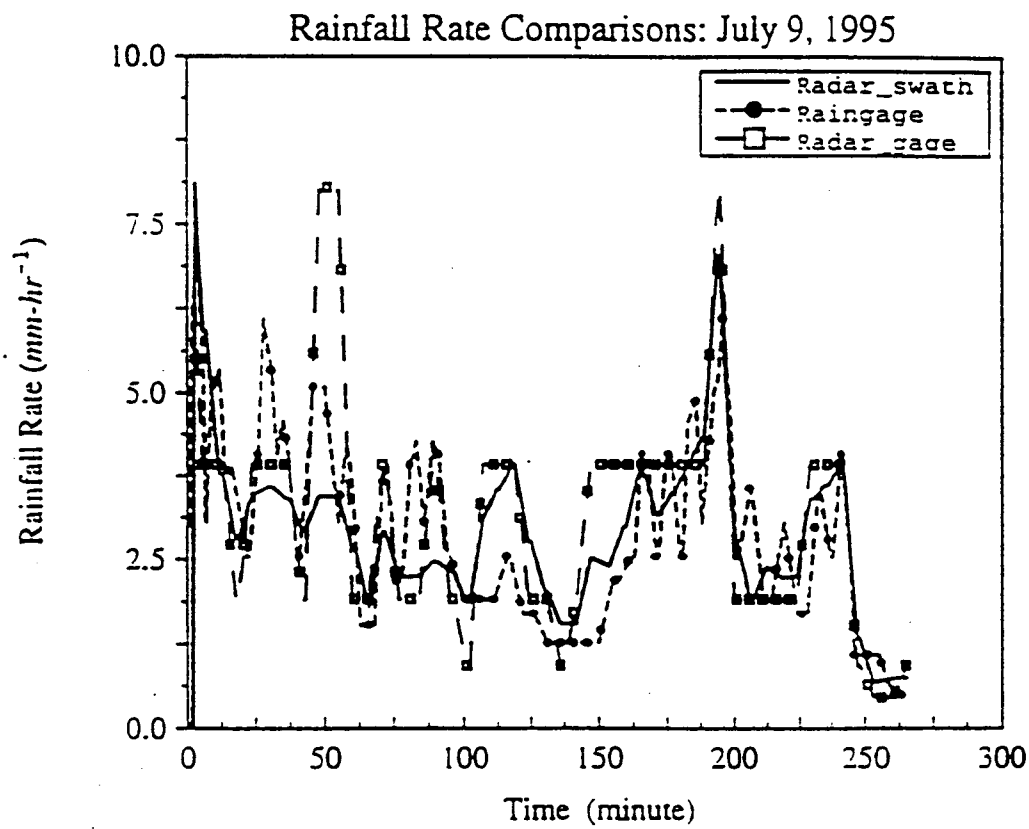

Figure 19. Radar-based estimates and rain gage measurements of rainfall rates at the University of Washington on July 9, 1995.

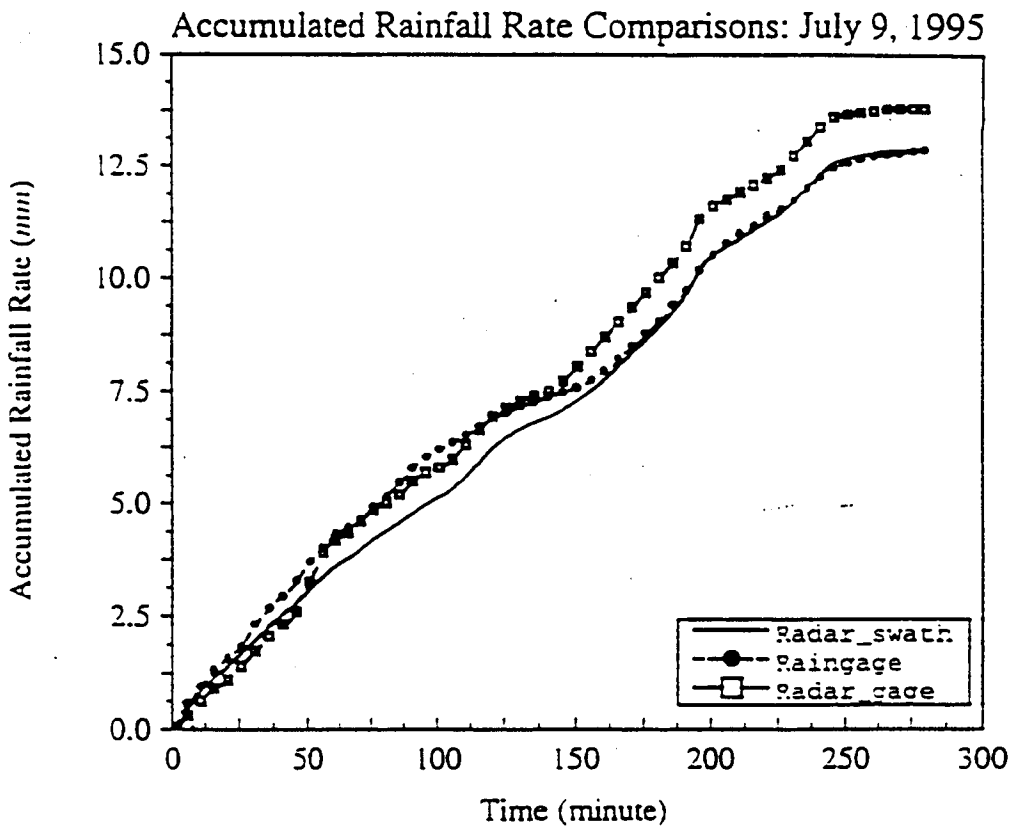

Figure 20. Rainfall accumulation comparisons between radar estimates and the rain gage located at the University of Washington for July 9, 1995.

Case Study II

This case study examined how the above weather-traffic indices can be applied as a tool in real-life situations. On April 19, 1996, at approximately 2:45 pm on I-5 in Tacoma, an accident resulted in three deaths. Investigators believed that the accident was partially caused by the unexpected driving conditions due to rainfall on the highway. Therefore, in this study, theaccumulated rainfall amount and the HWI were examined for the period surrounding the accident. These results are taken from Chen (1996).

The points of interest were those close to the path of I-5 near the Tacoma Dome accident site (see Figure 21). The primary region of interest (PRI) was a 33x33-km region centered around the location of the accident, which corresponds to pixels [320,218] to [352,250] in the radar image (Figure 21). The PRI was divided into nine sectors (11x11 km), for the swath analysis algorithm. used in the previous case study, to estimate the rainfall rate. The accumulated rainfall amount over the section of I-5 that was of interest is shown in Figure 22, with the rainfall at the time of the accident darkened. With this information, the time-distance Highway Wetness Indiex (HWI) contour could be determined for this time interval for the I-5 section. This is shown in Figure 23.

From figures 22 and 23, the following conclusions can be made about the *possible* weather-related causes of the accident. At the time of the accident, the northbound drivers were within an HWI minimum. Southbound drivers had just come from intense rainfall and very high relative HWI values. Southbound drivers may have begun to relax, becoming less alert. More importantly, however, northbound drivers felt that conditions were improving when farther ahead they were more severe. This may have caused a traffic slow down farther ahead that, being unexpected, caused someone to begin evasive action, which contributed to the beginning of the accident.

The above is only one of several plausible explanations for ways in which weather may have contributed to this tragic accident. It is not definitive by any means, but it points out how radar-based information can provide additional insight into accident reconstruction. Information gleaned from case studies such as this one could conceivably be used to educate, inform, and

forewarn drivers of potentially dangerous situations and thus significantly reduce the possibility of weather-induced accidents.

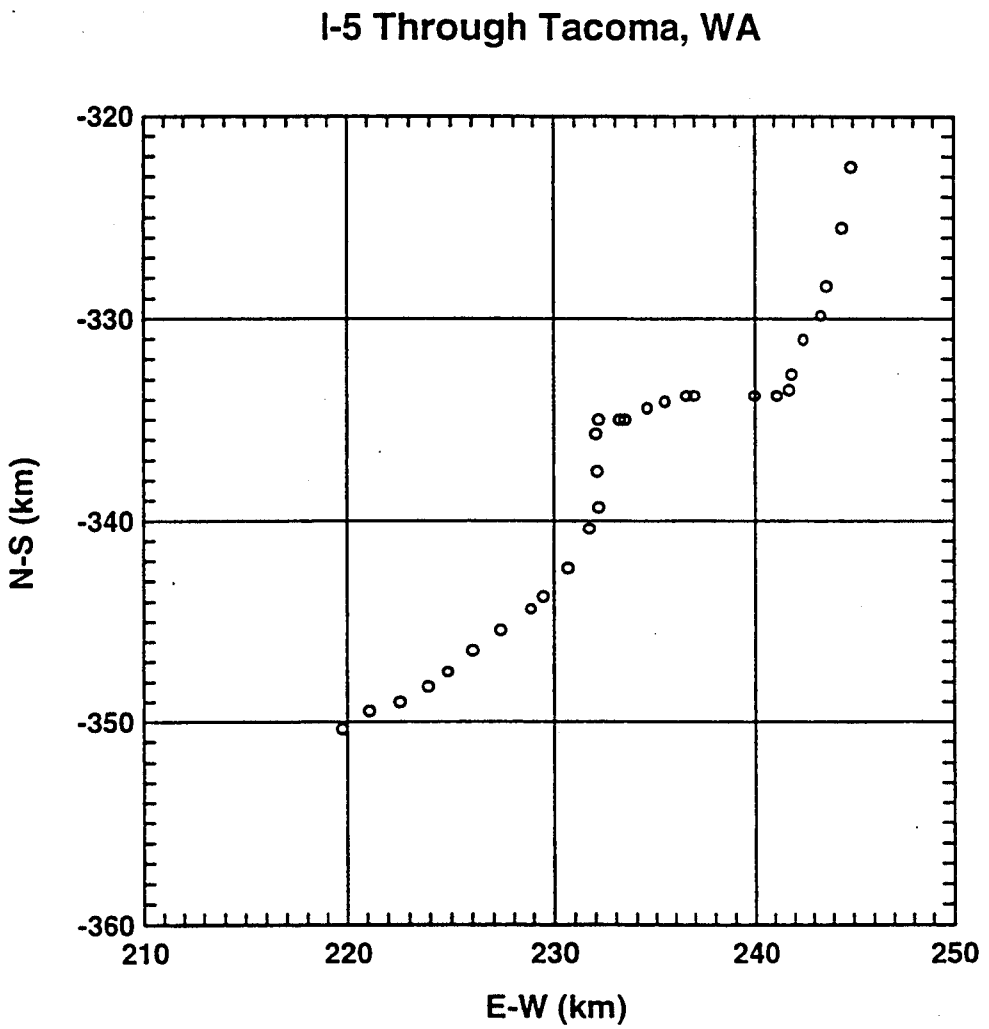

Figure 21. Path estimation points within the PRI used in the analysis.

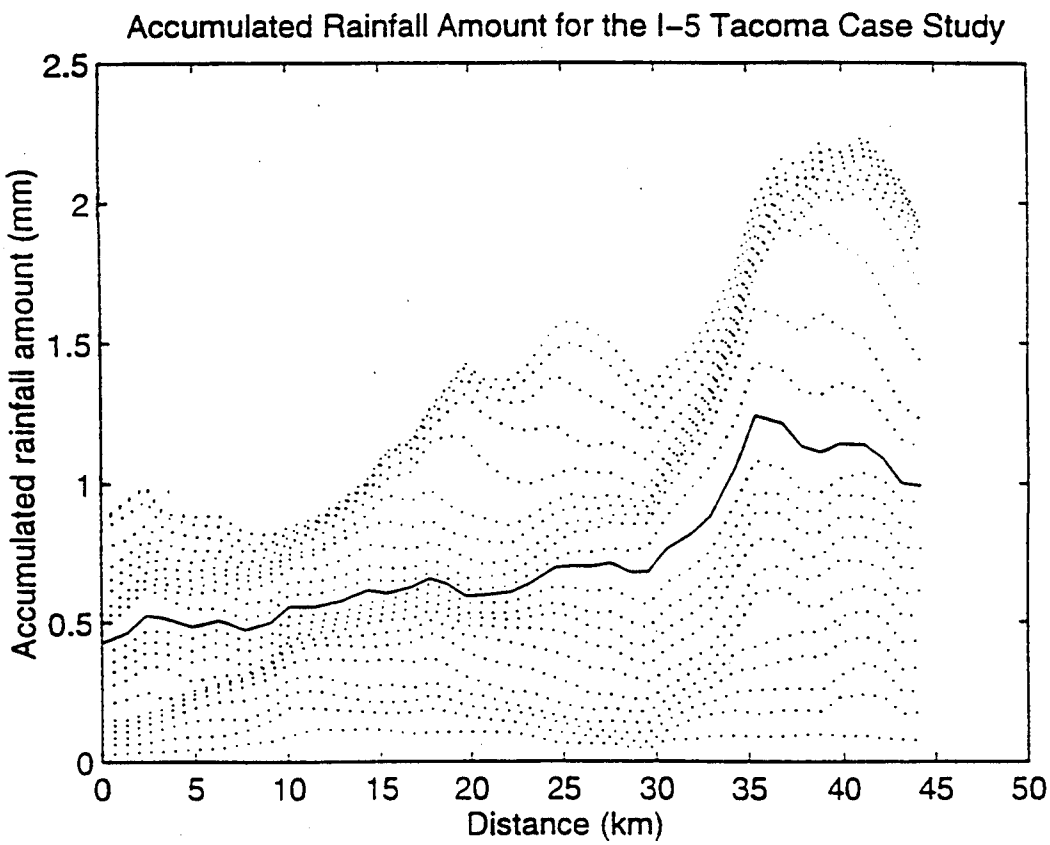

Figure 22. Accumulated rainfall amount for the I-5 Tacoma case study along the I-5 corridor. The accident occurred at 20.7 km at the darkened accumulation line.

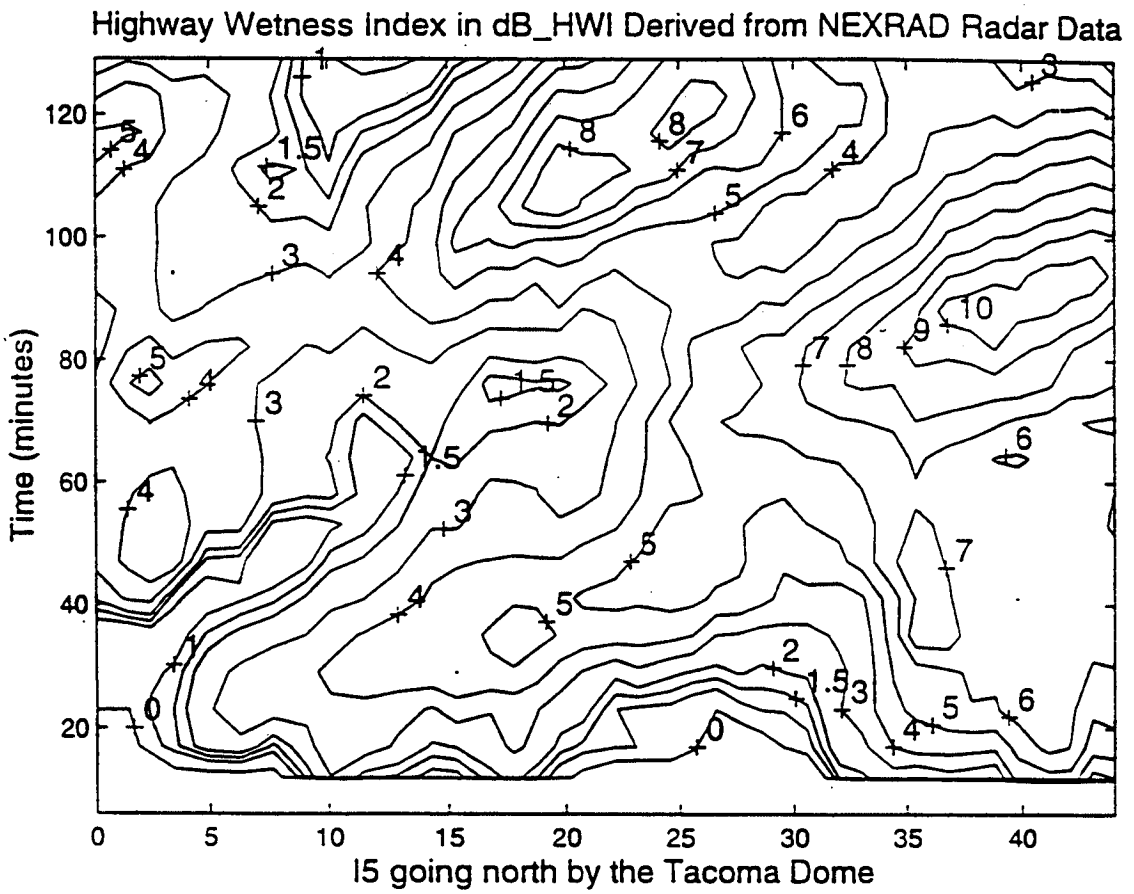

Figure 23. Highway wetness index in *db_HWI* derived from NEXRAD radar data (April 19,1996: 0 min=20:41 UTC). Contours are in steps of 2 dB.

CONCLUSIONS

The results of this investigation indicate that the NEXRAD weather radar (WSR-88D) holds great promise for assisting in the management of large urban ground-based transportation systems. The continuous flow of data on the temporal and spatial behavior of storms in real time should lead to not only better understanding of how weather affects traffic flow and related operations but also to enhanced understanding and knowledge of traffic-weather relationships. Eventually, this should lead to implementation of novel means for making utilization of the highway system better and safer, plus better design of modifications and/or additions to the system.

A method of utilizing the NEXRAD WSR-88D radar in the management of ground transportation systems in urban areas was demonstrated through the introduction of three rainfall-related indices, HWI, VII, and CHI. Contour plots of these for the I-5 north-south corridor through Seattle were used to demonstrate this potential. These were combined with traffic data that revealed how traffic slowdowns are related to weather phenomena.

Two case studies were undertaken: one to determine how reliable radar-based rainfall estimates are and another to determine whether the HWI can be related to a real-life accident. Both appear to have been successful. The radar estimates compared favorably with ground-based measurements. The HWI provided additional information into the weather-related causes of a fatal accident.

The results of this investigation illustrate that the NEXRAD system offers additional important societal benefits related to ground transportation systems. Indeed, much, if not all, of urban America stands to benefit from these applications—in terms of safer, more efficient, less congested highways (and waterways) and better design of highways.

RECOMMENDATIONS/IMPLEMENTATION

The final objectives of this study will necessarily have to await the results of further investigation. Of greatest importance will be demonstrations of the types of weather information that will be available and insights into how this information might be used to improve traffic management and other related ground transportation operations in the Puget Sound region. Also of importance will be the eventual means and costs associated with operational implementation of an appropriate data acquisition and analysis system. This will require close cooperation with other state agencies that have interest and need for NEXRAD-based information. For example, the Emergency Management Division of the Department of Community, Trade, and Economic Development was identified as having taken a leadership role for the state in this regard. Discussions with representatives of this agency and others will be useful to ensure that WSDOT will be well positioned to receive NEXRAD radar data, should it wish to implement the results of this project in any of its future transportation management strategies. Also, because significant other data are associated with traffic and its management, attention to integration of NEXRAD radar analysis products with these will be necessary. This can be achieved only through close cooperation with the cognizant offices of WSDOT, including the Seattle TSMC, plus state, county, and local government agencies.

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