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Weather Applications and Products Enabled Through Vehicle Infrastructure Integration (VII)

Feasibility and Concept Development Study

Prepared for:

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16. Abstract

Vehicle Infrastructure Integration (VII) involves the two-way wireless transmission of data from vehicle-to-vehicle and vehicle-to-infrastructure utilizing Dedicated Short Range Communications (DSRC). VII will enable the development of weather-related products and applications designed to improve safety and increase mobility and efficiency along the nation's roadways. This report examines current and future vehicle data elements that have the potential to be used directly or indirectly to sense weather and road conditions. The potential contribution of VII-derived atmospheric and road condition information in the analysis and prediction of weather-related hazards is also explored. To make effective use of mobile data for weather-related applications, it is necessary to invest in research to understand issues associated with current and anticipated data elements; therefore, VII-related research and development topics are surveyed, as well as the feasibility of utilizing VII-enabled data to mitigate the impact of road weather-related hazards.

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Acronyms

ABL - Atmospheric Boundary Layer
ABS – Anti-lock Braking System
AASHTO - American Association of State Highway and Transportation Officials
ASOS - Automated Surface Observing System
ATEC – Army Test and Evaluation Command
AWOS – Automated Weather Observing System
CASA - Collaborative Adaptive Sensing of the Atmosphere
DOD – Department of Defense
DOT – Department of Transportation
DSRC - Dedicated Short Range Communications
DSS – Decision Support System
EPA – Environmental Protection Agency
FHWA - Federal Highway Administration
FL – Fuzzy Logic
FOT – Field Operations Test
GB - Gigabyte
GPS - Global Positioning System
GMT – Greenwich Mean Time
HAR – Highway Advisory Radio
HRLDAS - High-Resolution Land Data Assimilation System
ITS – Intelligent Transportation Systems
MB – Megabyte
Mbit – Megabit
MDSS – Maintenance Decision Support System
MMW – Millimeter-Wave
MoWL – Mobile Wireless Laboratory
NAP – Network Access Points
NAS - National Academy of Science
NCAR – National Center for Atmospheric Research
NEXRAD - Next Generation Weather Radar
NRC - National Research Council
NWS – National Weather Service
OBE - On-board Equipment
OBU - On-board Unit
OEM - Original Equipment Manufacturer
RSE - Road Side Equipment
RSU - Road Side Unit
RTFDDA – Real-Time Four Dimensional Data Assimilation System
RWIS- Road Weather Information System
SDN – Service Delivery Nodes

TB – Terabyte
TOC – Traffic Operations Center
UMTRI – University of Michigan Transportation Research Institute
USDOT - United States Department of Transportation
VII - Vehicle Infrastructure Integration
VIIC - VII Consortium
WDT – Weather Data Translator
VMS – Variable Message Signs
WSR-88D – Weather Surveillance Radar - 1988 Doppler
Z - Zulu - Equivalent to Coordinated Universal Time (UTC)

1. Executive Summary

1.1 Objectives

Vehicle Infrastructure Integration (VII) involves the two-way wireless transmission of data from vehicle-to-vehicle and vehicle-to-infrastructure utilizing Dedicated Short Range Communications (DSRC). VII will enable the development of applications designed to improve safety and increase mobility and efficiency along the nation's roadways. The overarching goal of the VII initiative from a weather perspective is for the weather enterprise (defined as all the public and private organizations that collect, process, and generate weather products) to utilize vehicle data to improve weather and road condition products and to provide those products to transportation system decision makers, including travelers.

The utilization of data from mobile platforms is not new in the weather community, as ship-based observations have been used for more than a century. Data from aircraft have been used successfully for nearly a decade, and the number of parameters available from aircraft is expanding from primarily wind and temperature to humidity, turbulence, and icing. The utilization of data from vehicles poses significant technical challenges, particularly with respect to data quality; nevertheless, VII represents a technology that will significantly increase the density of weather observations in the Atmospheric Boundary Layer (ABL).

This report assesses the feasibility of using VII-enabled data to enhance road weather products. This is accomplished by providing a fundamental understanding of the weather-related vehicle data elements currently available on production vehicles, as well as anticipated data elements. Additionally, the potential contribution of these vehicle data to the diagnosis and prediction of weather-related hazards is examined. The report identifies technical issues and challenges related to the use of vehicle data, and it outlines a comprehensive list of research topics that will be essential for effective use of weather-related vehicle data. Finally, the report summarizes the feasibility of using VII data for road weather product development and improvement, and provides recommendations that will help ensure successful exploitation of vehicle probe data in weather applications.

1.2 Approach

The National Center for Atmospheric Research (NCAR) held two VII Weather Application Workshops to bring together experts from the automotive industry, VII Consortium, VII architecture and probe message processes development team, and the weather community. The overarching goal of these two meetings was to discuss and gather input related to the proposed VII architecture, probe message processes, potential data elements, possible road weather products, and the technical and scientific challenges associated with the use of these data.

The authors of this report attended several other conferences and symposia, which provided the opportunity to interact with different groups working on VII-related projects. In addition, the forums were used to update the VII community and others on the progress being made regarding the development of this report.

An extensive literature review was conducted as part of the report development process. The primary goal of the review was to acquire a deeper understanding of the envisioned VII architecture and probe message processes, as well as identifying potential weather-related vehicle data elements.

1.3 VII Deployment

The three principal elements that make up the VII system architecture are the On Board Equipment (OBE), Roadside Equipment (RSE), and the VII Network. Each vehicle that is a part of the VII system will be equipped with an OBE. The OBE contains the On Board Unit, which is responsible for transmitting and receiving data. Vehicle-to-vehicle and vehicle-to-infrastructure communication will be supported. The RSE, which will be located along the roadside, also will be capable of transmitting and receiving data. Public data received by the RSE will be passed along to the VII network and made accessible to data subscribers.

Two critical components of the VII deployment and implementation plan include RSE deployment and probe message processes. The strategies used to site RSEs, gather vehicle data, and transmit these data to the VII network are very important in terms of improving and generating road weather products.

The currently envisioned plan for siting RSEs includes criteria for both urban and rural deployment. Most importantly, the minimum spacing between RSEs will be 10 minutes at 60 mph for rural regions and 2 minutes at 20 mph for urban areas. It is likely that the RSE coverage resulting from these criteria will be adequate for application development in urban areas, but it may lead to the loss of data in rural regions. Data loss in urban domains will likely be offset by the shear number of vehicles transmitting data to RSEs. Moreover, ample RSE coverage will potentially exist across the eastern U.S., while the western states will likely experience significant gaps in RSE spacing.

The feasibility of using VII-enabled data in weather-related applications will be affected by two key aspects of the VII probe message processes: onboard buffer storage limitations (currently 30 snapshots) and snapshot hierarchy. Snapshots, which contain vehicle data elements valid at a specific point in time, are generated in one of three ways. Periodic snapshots are produced at prescribed intervals based on the speed of a vehicle, event-triggered snapshots are generated when the status of selected systems change or a predetermined threshold is met (e.g. ABS status change from “off” to “engaged”), and start/stop snapshots occur when a vehicle comes to a stop or begins to move. Note that all snapshots (whether event-driven, start/stop or periodic) contain all available weather elements. Event-triggered and start/stop snapshots have priority over periodic snapshots. This is an important aspect because under certain situations periodic snapshots could be deleted from the onboard buffer in favor of event triggered and start/stop snapshots. A set of periodic snapshots is more likely to contain correlated data that represent environmental and road conditions across a broader domain as compared to event-triggered and start/stop snapshots. Therefore, the deletion of periodic snapshots because of snapshot hierarchy could lead to the loss of important data.

Other aspects of the probe message processes that will limit the availability of vehicle probe data relate to privacy concerns. They include not allowing any identifying information associated with the vehicle or the vehicle’s operator to be transmitted as part of a snapshot, restricting snapshot generation for a certain distance after a vehicle is started, and deleting all snapshots when the vehicle is turned off.

1.4 Prospective Data

A number of data elements that could aid in road weather product improvements have been identified. These elements range from direct measurements of the environment (e.g. temperature) to elements that could be used to infer weather and road conditions (e.g. ABS). However, a significant amount of research will be required to fully understand how to effectively use vehicle-based data, as the characteristics of the data will vary greatly between vehicle manufacturers, vehicle models of the same manufacturer, and sensor types and models. It is unlikely that any single vehicle-based data element will be able to stand alone as truth, as there will be too many uncertainties about its quality and/or representativeness. Vehicle data will need to be processed in a statistical manner to address data outliers and to raise the overall confidence in data quality. The weather community has experience combining multiple disparate datasets to derive products. Vehicle data will have to be treated in a similar manner. Even with those caveats and concerns, vehicle data will result in the generation of improved weather and road condition analysis and prediction products because of the large volume of data, distribution of observations, and frequent update rates.

1.5 Data Efficacy

Data from vehicles operating in the Detroit Metropolitan region were acquired from DaimlerChrysler. These data contain information on vehicle location, observation time, wiper state, barometric pressure, and air temperature. Vehicle data elements were compared to NEXRAD Doppler weather radar data and observations from surrounding stationary weather stations. These case studies were promising, as a good correlation between vehicle data elements, radar data, and surrounding surface observations existed. In one case, vehicle data responded to an outflow boundary that was generated by a nearby thunderstorm. These case studies support the idea that vehicle data could play an instrumental role in enhancing road weather applications and products.

1.6 VII-enabled Improvements

A number of weather and road products will be improved with vehicle data including improvements in both the diagnoses and prediction of weather and road condition hazards. Examples of improvements are supplied in Table 1.1, but they only provide a sampling of what may be possible with these new datasets.

Table 1.1 VII-Enabled Road Weather Product Improvements

Potential Weather and Road Condition Improvements	
Weather Improvements	**Road Improvements**
Reducing radar anomalous propagation (AP)	Improved identification of slippery pavement
Improved identification of virga (precipitation not reaching the ground)	Improved knowledge of pavement temperatures
Improved identification of precipitation type	Improved knowledge of pavement condition (dry, wet, snow covered, etc.)
Improved identification of foggy regions	Improved input data for surface transportation decision support systems such as the Maintenance Decision Support System (MDSS) and future decision support systems that will serve traffic, incident, and emergency management, and non-winter maintenance
Improved characterization of surface conditions for weather models	
Improved weather analysis and prediction in complex terrain	
Improved air quality monitoring and prediction	
Improved ability to derive boundary layer water vapor from radar refractivity	

VII technology will not only enable vehicles to communicate probe data to external systems, but it will enable safety and mobility related products to be delivered to vehicles. When drivers enter their vehicles, they are usually cut off from normal information sources such as television and the Internet, and until cell phone technology became dominant, phone service was unavailable. Wireless communication technologies are becoming more reliable, more widespread, and less expensive, which provides an enormous opportunity for the automotive, consumer electronics, and telecommunication industries. The widespread adoption by the public of wireless vehicle technology is just around the corner. In-vehicle weather and road condition products that are likely to be of the most interest to drivers are presented in Table 1.2.

Table 1.2 In-Vehicle Road Weather Products

In-Vehicle Weather and Road Condition Products	
Heavy Rain	Hail
Heavy Snow	Dense Fog
High Winds	Tornadoes
Severe Thunderstorms	Blizzards
Icy Conditions	Flooding
Smoke	Blowing Dust
Light to Moderate Precipitation	Road Frost
Drifting Snow	Lightning

In-vehicle information systems that couple navigation technologies with dynamic weather and road condition information may also help consumers justify their contribution to the national VII dataset. Vehicle owners may be more willing to provide vehicle data if they know that they will be a direct beneficiary of the data. In-vehicle weather and road condition safety and mobility products may provide that justification.

1.7 Data Processing

The amount of data that could potentially flow through the VII infrastructure could be immense. It is likely that many prospective users will not be capable of handling the vast quantities of data that are expected. Additionally, it is unlikely that some users will be able to contend with the complexities associated with the data, such as data quality, representativeness, and format. Applications (middleware) will need to be implemented that will facilitate the use of VII data. Without such a function, the feasibility of utilizing vehicle probe data will be lower and there will be substantially more risk in its use.

One solution for addressing this issue is to utilize a Weather Data Translator (WDT) to preprocess weather-related vehicle data before they are distributed to data subscribers. Raw data would still be made available to users that wish to obtain unprocessed data. The WDT would be made up of three primary components: filtering, quality checking and translation. The proposed WDT would acquire, parse, and process vehicle probe messages. Prior to a quality checking process, data would be filtered to extract data that are known to be unrepresentative.

Standard quality checking algorithms (e.g., outlier, format, bounds, and spatial tests) as well as quality checking algorithms specifically developed for VII data would be included as part of the WDT. Finally, the WDT would also demonstrate the ability to translate VII data into statistical samples that represent chosen parameters over a selected region and time.

1.8 Data fusion

The lack of consistently accurate road weather hazard products is the result of several factors including a limited surface observation network, an inadequate understanding of the physical mechanisms responsible for some road weather hazards, and a need for improvements in weather and road condition modeling, particularly with respect to clouds and precipitation. VII will facilitate improvements in all of these areas; however, due to the complexities and uncertainties associated with VII-enabled data, several challenges and deficiencies must be overcome. Therefore, it is important that advanced data fusion techniques be developed and implemented to maximize the benefits of VII data for road weather applications.

1.9 Research Requirements

VII holds considerable promise in supporting the development of weather-related products for the surface transportation community. However, it is evident the use of VII-enabled data for product development and enhancement will be beset with challenges. In order to make effective use of mobile data for weather-related applications, it will be necessary to invest in research to understand issues associated with the use of current and anticipated data elements. VII-related research and development topics that are necessary to support the development and improvement of weather-related products include, but are not limited to:

- Data Fusion Techniques
- Data Quality and Accuracy

- Quality Checking
- Human Factors
- Numerical Modeling Using VII-enabled data
- Data Processing

The research needs are discussed more thoroughly in the main body of this report.

1.10 Conclusions

The authors believe that it will be feasible to utilize VII-enabled vehicle probe data in the generation of weather and road condition products and that these new datasets will improve roadway safety, mobility and efficiency. However, to ensure the success of the VII initiative from a weather perspective, several recommendations are provided. They include: (1) having experts from the meteorological community take an active role in helping to guide selected aspects of the VII program such as the proposed strategies for RSE deployment and probe message processes; (2) developing a Weather Data Translator (WDT) to facilitate the use of weather-related vehicle probe data; (3) Investing in research that will support effective use of current and anticipated weather-related vehicle data elements; (4) refraining from attempting to use weather-related VII data elements as stand alone truth; (5) conducting extensive research on the vehicle data elements of interest in an effort to ensure the proper use of those data including, if possible, collaborating with multiple OEMs that design and implement the sensors or devices from which the data originate; and (6) initially targeting basic applications and products that can be improved or constructed with rudimentary vehicle data elements.

2. Introduction

THE NEED FOR ENHANCED ROAD WEATHER INFORMATION

An investigation of crashes occurring from 1995 through 2004 revealed that each year there are over 1,500,000 crashes that occur during poor weather conditions, resulting in more than 690,000 people injured and nearly 7,400 fatalities *(1)*. It is worth noting that these figures are considerably higher than any other mode of transportation (e.g. aviation, rail, marine, etc.). The majority of the weather-related crashes (76%) occurred when roadway surfaces were wet, while 10% of all weather-related crashes took place during snowy or slushy driving conditions.

Adverse weather not only affects safety, but leads to degradations in mobility and efficiency. Depending on the time of day and the weather conditions, traffic flow along signalized arterials can be reduced anywhere from 6% to 30% during adverse weather. Additionally, vehicle speed is reduced by 10% to 25% when conditions include wet pavement and rain. During situations when roads are snow covered and/or slushy, vehicle speeds can decline as much as 40% *(2,3)*. As might be expected, flow rate degradations and speed reductions directly contribute to increased travel times. Under extreme conditions (e.g. snowstorms), travel times can increase by as much as 50% *(2)*.

In an effort to mitigate the impact weather has on the national roadway system, several recent reports *(4,5,6)* have highlighted the need for:

- a vigorous road weather research program aimed at understanding road weather phenomena and the effect of weather on safety, capacity and efficiency;
- improved modeling capabilities and forecast systems;
- an integrated observation network and data management system;
- enhanced delivery and communication of road weather information;
- and new technologies to improve weather and road condition analyses and forecasts.

Vehicle Infrastructure Integration (VII), which involves vehicle-to-vehicle and vehicle-to-infrastructure communications through Dedicated Short Range Communications (DSRC-wireless radio communication at 5.9 GHz), has the potential to facilitate advancements in each of these areas, possibly fostering improvements in the accuracy and timeliness of road weather information. Such improvements could also translate into new and improved decision support tools and products for the surface transportation community.

There is a critical need for high-resolution (spatial and temporal) atmospheric and road condition data. These data should include measurements of parameters within the atmospheric boundary layer (ABL)[1], as well as surface and subsurface measurements. VII will enable direct measurement of select atmospheric variables and indirect assessment of road conditions at high spatial and temporal frequencies. Together this information will lead to advanced road weather analyses and forecasts, and it would advance the state of understanding as it relates to how weather and road conditions impact the U.S. roadway system.

[1] The lowest layer of the troposphere where air flow is influenced by friction of the Earth's surface. The atmospheric boundary layer, on average, ranges from the surface to approximately 1 kilometer (3,300 feet).

In terms of improving road weather forecast capabilities, the availability of VII-enabled data may result in substantial improvements in the ability of numerical weather prediction models to accurately forecast changes in the atmosphere, including the ABL. Accurate forecasts of atmospheric boundary conditions are dependent on four primary factors: the spatial resolution of the weather prediction model; the effective simulation of atmospheric dynamics at various scales; the physical parameterization scheme used to characterize surface and turbulent processes; and the ability to accurately analyze the initial atmospheric structure and surface parameters *(7)*. While the capacity of numerical models to forecast surface conditions is reliant on more than simply defining the initial state of the atmosphere, it is clear that an accurate characterization of the atmospheric conditions is an important element in the prediction process. Coupling improvements in atmospheric numerical models with soil models that track the energy and water budget will also directly benefit road condition forecasts.

It is anticipated that data derived from vehicles and transmitted to the VII infrastructure will be made available to integrated observation networks and data management systems. For example, it is envisioned that weather and road condition related vehicle data elements will be included in the *Clarus* system, a network designed to collect, quality check, and disseminate atmospheric, hydrologic, and pavement data through on-demand and subscription-based services *(8)*. The *Clarus* system is part of a larger initiative sponsored by the Federal Highway Administration (FHWA) dedicated to acquiring, organizing and distributing roadway environmental sensor station data in support of diagnosing and predicting atmospheric and road conditions that impact the surface transportation community.

VII presents a new technology that will improve road weather information and products by facilitating the communication of weather and road condition data to and from vehicles and other transportation decision support systems and stakeholders. In-vehicle information systems, the national 511 traveler information system, traffic management centers, traffic operation centers, maintenance managers, dispatch operations, and others should benefit from VII-enabled data and related applications. In terms of weather-related information and products, the VII architecture should lend itself to providing raw data, post-processed data, and application based solutions to stakeholder communities.

The goals of this report are to: (1) provide a basic understanding of current and future vehicle data elements that have the potential to be used directly or indirectly to sense weather and road conditions; (2) examine the potential contribution of VII derived atmospheric and road condition information in the analysis and prediction of weather-related hazards; (3) identify technical issues and barriers that may impact the development and implementation of weather-related VII applications; (4) outline research topics that need to be addressed to fully utilize vehicle data in improving road weather products and services; and (5) summarize the viability of utilizing VII-enabled data in weather and road condition applications designed to improve surface transportation safety, mobility, and efficiency.

This document contains forward-looking statements regarding the use of VII-enabled data in the development of road weather products and applications. The assertions made herein are based in part on the current state of understanding as it relates to the VII architecture, probe message processes, and surface transportation weather. There are a number of important known and unknown risk factors and uncertainties that will affect the beliefs, ideas and claims expressed herein, some of which are described in detail.

3. Methods

REPORT DEVELOPMENTAPPROACH

During the course of this study, The National Center for Atmospheric Research (NCAR) held two VII Weather Application Workshops/Expert Panel meetings. These took place during the first half of 2006. The workshops were designed to bring together experts from the automotive industry, VII Consortium, VII architecture and probe message processes development team, and the weather community. The overarching goal of these two meetings was to discuss and gather input related to the proposed VII Architecture, probe message processes, potential data elements, road weather products, and the technical and scientific challenges associated with the use of VII data. Information captured during these discussions has been used to shape the contents of this report. Notes from these meetings are contained in Appendices A and B.

In an effort to track VII advancements, the authors of this report attended several other conferences and symposia including national and international conferences such as the Transportation Research Board (TRB), American Association of State Highway and Transportation Officials (AASHTO), and the Intelligent Transportation Society of America (ITSA) annual meetings, 2005 ITS World Congress, the 2005 VII Public Meeting in San Francisco, and the 2005 Travelers Information Workshop held in Arlington, VA. These meetings provided the added opportunity to explore VII from the perspective of the private sector. Interactions with private sector vendors helped to shed light on the kinds of weather-related applications they felt would be beneficial for their customer base. Finally, these meetings were used as a means to update the VII community and others on the progress being made regarding the development of this report.

In addition to interactions with VII experts, an extensive literature review was conducted to further gain an understanding of the currently envisioned VII architecture and probe message processes. This review also aided in the identification of potential weather-related vehicle data elements and their characteristics. Each one of these factors will have a significant influence on the role VII could play in road safety and mobility improvements, especially as it relates to road weather hazards.

Throughout this investigation, NCAR developed several positive relationships with outside organizations. One of the most notable is with DaimlerChrysler. Like many automotive manufacturers, DaimlerChrysler is investigating the process by which data from vehicles can be gathered and transmitted to infrastructure in support of product development. In doing so, DaimlerChrysler has built up an archive of vehicle data acquired primarily in the Detroit Metropolitan area. A subset of these data was provided to NCAR. Weather-related data elements contained in the dataset include wiper state, temperature, and barometric pressure. As a result, NCAR has been able to carry out subjective analyses of these data and further explore the potential contribution of VII-enabled data to weather application and product development (see section 6).

4. Technical Background

VII ARCHITECTURE, PROBE MESSAGE PROCESSES AND THEIR IMPACT ON VII-ENABLED DATA

This report discusses the feasibility of using VII data to construct and improve weather-related applications and products. The details and complexities of the VII architecture and probe message processes are not discussed here in detail, but it should be noted that the possibility of using vehicle data for road weather products will depend on the final VII architecture and probe message processes design. For continuity, a synopsis of relevant components of the architecture and probe message processes is provided; however, the reader is encouraged to consult the documents that are referenced in this section of the report for further information. Details associated with the VII architecture and probe message processes are still evolving.

4.1 VII Architecture

The VII program is a cooperative effort involving the U.S. Department of Transportation (USDOT), automobile manufacturers, the American Association of State Highway and Transportation Officials (AASHTO), and several state departments of transportation. Together these stakeholders are working to define, develop, and deploy a nationwide system that would enable vehicle-to-vehicle and vehicle-to-infrastructure communications through dedicated short range radio technology (DSRC-wireless radio communication at 5.9 GHz) *(7)*. For some time, it has been realized that such a system would support the development and implementation of critical safety applications such as intersection violation, hazardous weather warnings, hazardous pavement condition warnings, lane departure, curve speed warning, and collision notification warnings. Other examples of applications that could be supported by the VII framework include signal timing optimization, traffic and congestion measurements, and electronic toll payments. Although these applications are less critical compared to safety applications, they would contribute to improving mobility and efficiency.

The VII concept is based on the idea of using vehicles as probes. As vehicles traverse the nation's roadways, they will measure and collect a variety of information ranging from on-board diagnostics (e.g., emission system status) to measurements of the environment (e.g., air temperature). When a VII-enabled vehicle comes within range of the roadside receiver, selected data elements will be wirelessly transmitted to the roadside, routed to the VII network, and made available to data subscribers. Vehicles will also exchange critical safety information when they are within range of one another. This process of information delivery and exchange will enable the development and deployment of safety and mobility related applications as well as new commercial applications. A critical component in the application development process is understanding how vehicle data elements are produced, stored, and transmitted from the vehicle to the infrastructure.

Figure 4.1 shows the three primary elements that make up the VII system architecture: On Board Equipment (OBE), Roadside Equipment (RSE), and the VII Network. It is envisioned that each VII-enabled vehicle will be equipped with OBE that includes an On-Board Unit (OBU - which is a DSRC transceiver), application processors, GPS system, human machine interface, and vehicle services interface *(9)*. The OBU is responsible for communications between the vehicle and RSE, as well as vehicle-to-vehicle communications. Vehicle probe messages stored on the vehicle are transmitted to RSEs and other vehicles via the OBU. The OBU is also capable of receiving messages from the infrastructure and other vehicles. An important aspect of the VII communication model is that vehicle-to-vehicle and vehicle-to-roadside communication is not continuous. A vehicle (i.e. its OBU) will only communicate with a roadside unit or another vehicle if it is within range. The vehicle-to-roadside and vehicle-to-vehicle transmission range will be approximately 300-400 ft (91-122 m), depending upon the FCC power restrictions *(9,10)*.

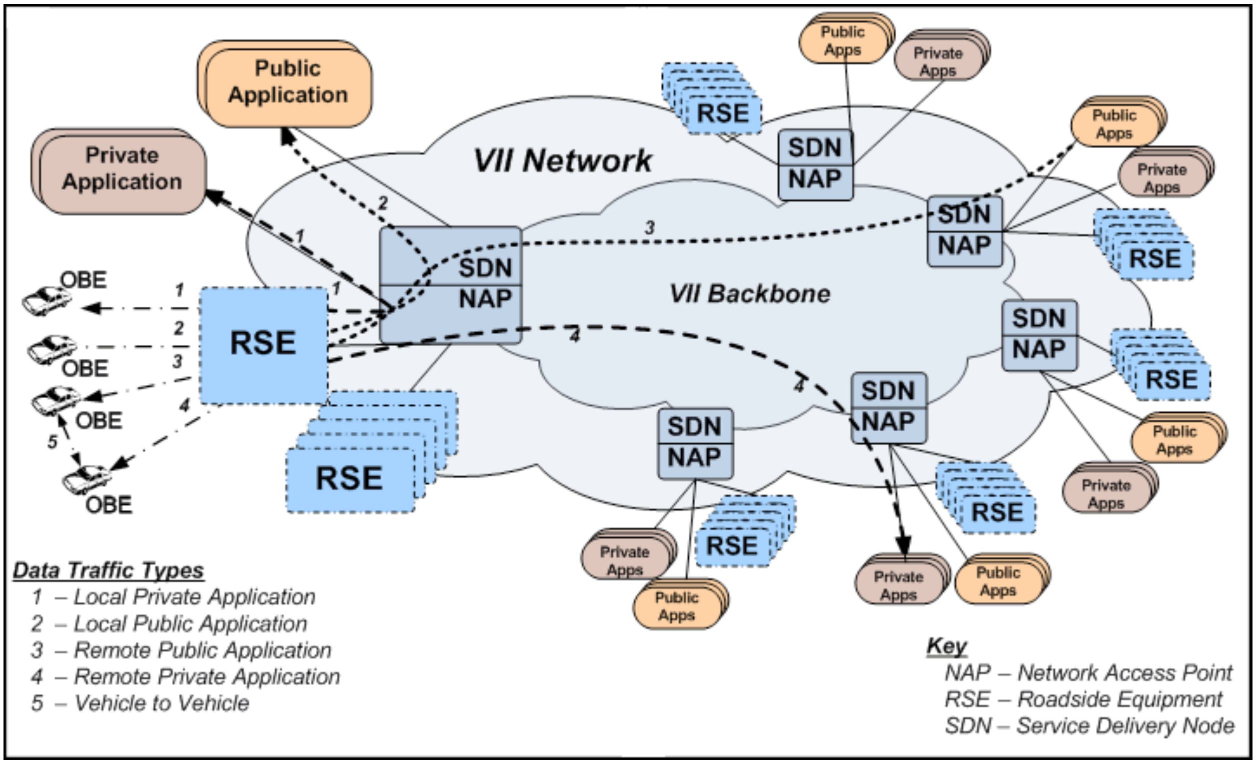

FIGURE 4.1. Representation of VII Network Architecture (courtesy of Booz Allen Hamilton)

Similar to the OBE, several components make up the RSE: a transceiver, an input/output controller, a router for VII network access, a GPS receiver, and application processor. Most importantly, the transceiver, or Roadside Unit (RSU), can transmit to and receive data from vehicles within its range *(9)*. In many cases, RSEs will be located at intersections to take advantage of signal controller electronics and provide situational monitoring for local safety applications. Currently, it is estimated that over 450,000 RSEs will need to be deployed to obtain national network coverage.

An example of rural RSE coverage showing RSE locations at national highway system intersections and interstate interchanges is supplied in Figure 4.2. In terms of mature nationwide RSE deployment, a distance of 10 miles will separate RSEs in rural areas, while RSEs will be spaced every 0.6 miles in urban areas[2]. In order to adhere to the 10 mile spacing requirement in rural areas, additional RSEs will need to be deployed beyond what is presented in Figure 4.2. Nonetheless, Figure 4.2 demonstrates the fact that the coverage in the eastern portion of the United States will be more comprehensive when compared to the Great Plains and Rocky Mountain states. Furthermore, RSE density will be proportional to population density; this will have implications on the quality and quantity of observations available in urban and rural settings.

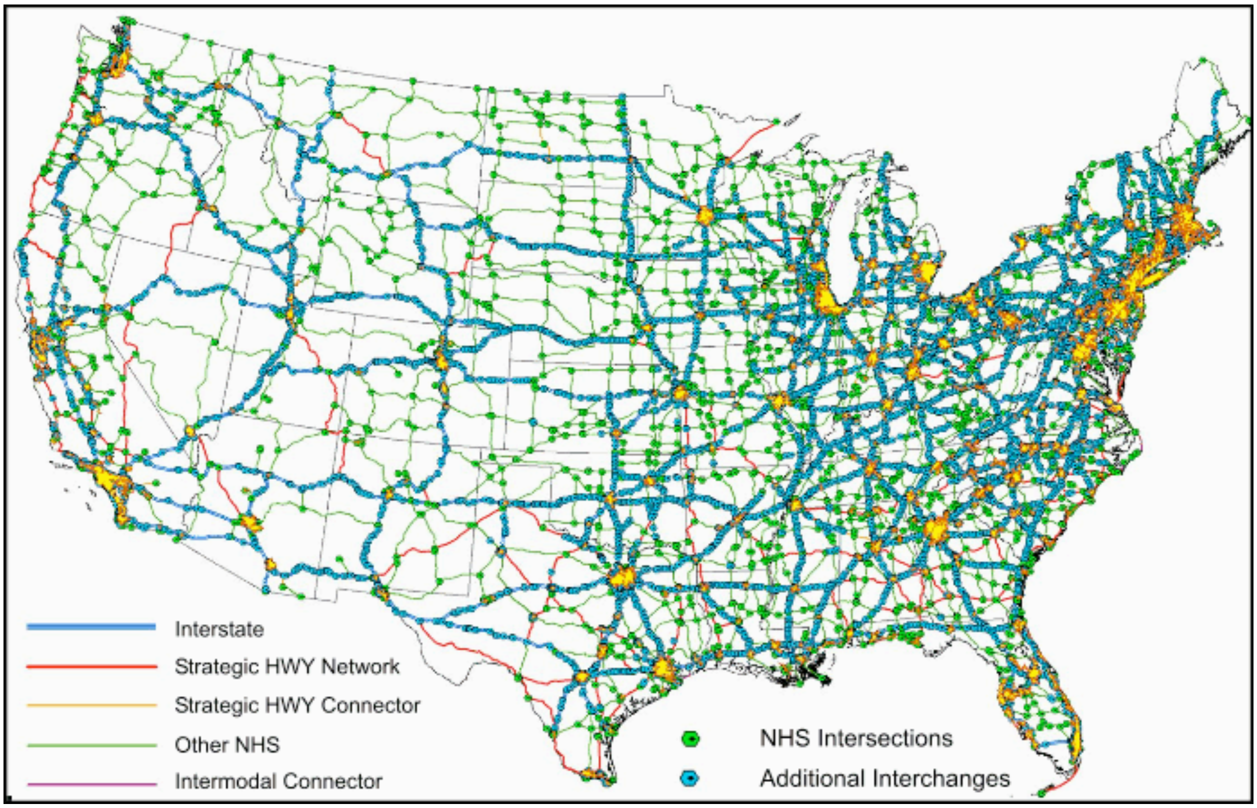

FIGURE 4.2. Potential rural RSE deployment based on national highway system intersections and interstate interchanges. ***(12)***

The VII Network, which includes network access points (NAPs) for the delivery of data to and from RSEs, is characterized in Figure 4.1. The network will also serve to route data to the appropriate data subscribers via service delivery

[2] The current probe message processes, which are discussed in section 4.2, were founded on the assumption that the minimum spacing between RSEs will be 10 minutes at 60 mph for rural regions and 2 minutes at 20 mph for urban areas *(10,11)*. This equates to a distance of 10 and 0.6 miles for rural and urban areas, respectively.

nodes (SDNs). Data flowing through the VII Network will be classified as public or private; thus, applications created from these data can also be seen as public or private. Data that are passed between vehicles and to automobile manufacturers will be considered private, and they will not be available to the general public. In addition, data exchanged between vehicles and some commercial service providers will also be classified as private. All other data will be available to subscribing users such as traffic operation personnel (TOCs), maintenance managers, dispatch operators, etc.

As previously indicated, bi-directional data flow will exist in the system. For example, public messages that relate to safety may be sent through the network to a specific RSE, and the roadside unit will broadcast this information to vehicles within its range of communication.

4.2 Probe Message Processes

In this section, a high-level description of current ideas and concepts for processing probe messages is presented for reference. A probe message is a specific message that is transmitted from a vehicle to an RSE. The methodology for collecting and transmitting probe data to and from vehicles is still being developed by VII program participants, so concept refinements are anticipated.

According to the current thinking, probe data collected by vehicles will be categorized into two groups: periodic and event-driven. Periodic data represent elements that are routinely available for collection. Outside air temperature and vehicle speed are two examples of periodic data. In contrast, data resulting from anti-lock brakes or stability control activation are examples of event driven data elements. Information associated with these systems is available on an irregular, event driven basis.

Vehicles have the potential to provide an inordinate amount of data to the VII network; however, the use of DSRC as the conduit for data transmission does put some constraints on the system. To make effective use of VII communication bandwidth and ensure that the system will not be overburdened with data transmission issues, standardized processes for data collection, prioritization and transmission are being defined.

By the current definition, a snapshot is a collection of vehicle data elements (e.g. temperature, wiper, and light settings) valid at a specific time. The concept is that a maximum of 30 snapshots will be stored on a vehicle at any one time; however, this number is subject to change. Snapshots can be generated in three ways: periodically, event triggered or by vehicle starts and stops *(10,11)*. Periodic generation will occur at prescribed intervals based on the speed of a vehicle as it moves between RSEs. A vehicle traveling at 60 mph or greater will generate snapshots every 20 seconds, while a vehicle traveling at 20 mph or less will generate snapshots every 4 seconds. Interpolation is used to determine the snapshot interval when the vehicle speed is between 20 and 60 mph *(10,11)*. These thresholds were selected in an attempt to evenly distribute snapshots between RSEs. A change in the status of some vehicle systems or surpassing a predetermined threshold associated with certain data elements will initiate an event-triggered snapshot. For example, changes in the traction control system status (e.g. "off" to "on") will result in a snapshot. Finally, when a vehicle begins moving or comes to a stop[3], a snapshot will be generated. Independent of what method results in a snapshot, all available vehicle data elements will be included in the snapshot.

As noted earlier, the on-vehicle snapshot storage capacity will be limited. Event-triggered and start/stop snapshots will take precedence over periodically generated snapshots. In some situations, it is likely that periodic snapshots will be deleted from the on-board buffer in favor of event-triggered or start/stop snapshots. Additionally, the buffer space available for periodically generated snapshots will depend on the number of event-triggered and start/stop snapshots occupying the buffer space. The storage of periodic snapshots is based on a first in/first out methodology. If the buffer is full of periodic snapshots and another periodic snapshot is generated, the oldest snapshot in the buffer will be erased to make room for the new snapshot. Conversely, no event-triggered or start/stop snapshots will be erased (unless the buffer is full of these types of snapshots) until the vehicle is in range of an RSE and the data are transmitted to the RSE. If the buffer is limited to 30 snapshots and there are 13 event-generated snapshots, then there will be space for 17 periodic snapshots. Once the buffer is full and another event or start/stop snapshot is generated, the oldest periodic snapshot will be erased.

Generally, weather-related applications and products utilize observations that can be linked to known platforms and sensors. This will not be the case for VII data. No identifying information related to the vehicle or the vehicle's operator will be transmitted as part of a snapshot. Under the current design, the only descriptive information related to the origin of a snapshot will be a vehicle type data element and a temporary identifier (ID). Vehicle type will be used to define the class of the vehicle (e.g. passenger car, bus, truck, etc.) (9). No data concerning the make and model of the vehicle will be made available. A random temporary ID will be linked to the snapshots. This ID will be updated

[3] Start/Stop snapshots are based on well-defined criteria. A vehicle is considered stopped when no other stops have occurred within the last 15 seconds and there has been no vehicle movement for 5 or more seconds. A start is considered to take place when the vehicle's speed exceeds 10 mph *(11)*.

when the vehicle first comes within range of an RSE, and it will be regenerated after 120 seconds or 0.62 miles (1 km), which ever comes first *(11)*.

Other aspects of the probe message processes that will influence the creation of applications and products include the proposed practice of restricting snapshot generation for the first 1640 feet (500 meters) after a vehicle is started, and the proposed standard of deleting all snapshots when the vehicle is turned off *(11)*.

4.3 Implications of Probe Data Collection and Dissemination Processes

The manner in which vehicle data elements are generated, stored, transmitted, and disseminated to product developers will affect the types and quality of products that can benefit from VII-enabled data. This section highlights how the currently envisioned RSE deployment and probe message processes may influence data availability and the development of weather-related products.

A depiction of RSE deployment in rural regions is presented in Figure 4.2. As discussed, the current probe message processes were constructed under the assumption that rural RSE spacing would be 10 miles; therefore, it is likely that some of the RSE gaps displayed in the figure will be reduced. Nonetheless, the VII infrastructure deployment will not occur overnight; it will take several years before reaching a state in which RSEs are located at 10-mile intervals in rural areas and 0.6 miles apart in urban areas. In some situations, data will be lost. For example, in a rural environment where the RSEs may be widely spaced, vehicle data will likely be clumped around RSEs as older data will be eliminated from the on-board data buffer. This design result means that users of the vehicle data should not expect the data to be evenly spaced along roadways, particularly in rural areas. This factor could very well determine what kinds of weather-related applications could be produced using vehicle data, as well as the accuracy of some VII-enabled products. The meteorological community has long relied upon stationary surface observations (e.g. ASOS) with relatively coarse spatial resolution. VII will provide data that would fill in these gaps, but the possibility of data clustering around RSEs would limit the usefulness of these data in some applications.

The loss of data will not only be an issue in rural regions, but it will be concern in urban areas as well. In terms of weather-related data elements, it will be important to maximize the spatial distribution of data between RSEs. Though event-triggered and start/stop snapshots could supply vital information concerning atmospheric and road conditions, collections of periodic snapshots gathered from vehicles will contain data over a larger domain, thus providing more detail about the spatial variations of particular variables. A vehicle encounter with a heavily congested roadway could result in the generation of both periodic and start/stop snapshots. It is possible that previously collected periodic snapshots contained in the buffer could be deleted before an OBU has the opportunity to transmit data to an RSU. In some cases, the deleted snapshots will not only provide data over a greater stretch of roadway, but they may contain more accurate measurements of certain parameters than the more recent snapshots gathered while the vehicle is in heavy traffic (e.g. temperature [see discussion in section 5.1]).

Restricting the initial generation of snapshots until the vehicle has traveled 1640 feet after the vehicle's engine is started, as well as deleting the on-board buffer when the vehicle engine is turned off, will result in the loss of data. Protecting the privacy of the vehicle operator is a high priority, and these probe message strategies may help to ensure that an individual cannot be tracked to a location such as their home or office. However, there may be instances when these strategies restrict data element production or cause data to be purged. For example, there will be times when an individual stops at a store to buy groceries or a gas station to refuel. When the vehicle's engine is turned off, all of the data stored in the on-board buffer will be lost. When the vehicle resumes its trip, it will not produce probe data for another 1640 feet, even if the vehicle encounters an icy intersection and an ABS event occurs. In these types of situations, data that could be used in the analysis and diagnosis of weather and road condition hazards will be lost. Another factor that may result in the loss of data is the fact that a vehicle will only transmit one set of snapshots from the onboard buffer while in range of an RSU. Thus, if additional snapshots are collected while the vehicle is still within range of the same RSU, they will not be transmitted until the vehicle comes into range of another RSU. Not only could this delay the transmission of critical data, but it could also lead to data loss under certain situations (e.g. high traffic). Overall, the potential for data loss will be more critical in rural environments as compared to urban areas, as urban corridors will have a large enough number of reporting vehicles to compensate for such data losses.

Meteorological applications are generally constructed with a great deal of knowledge about the stations from which data are obtained. Not only does an application developer have information about the location and time of the observations, but metadata containing information about the station, including its unique identifier, can be obtained in most instances. This will not be the case with VII-enabled data, and this will present several challenges for developers. The level of maintenance from one vehicle to the next varies greatly; therefore, there will be times when bad data from a malfunctioning vehicle sensor will be transmitted to RSEs and sent on to the VII network. There will not be a way to track this vehicle in an effort to filter out the bad data. The vehicle will repeatedly send erroneous data to the network until the vehicle owner has the vehicle serviced, which may still not ensure that the problem is caught and corrected. For this reason, it will be necessary to have effective quality checking procedures in place for VII data. One method of ensuring data quality is through a Weather Data Translator (see section 8). Knowing the type and location of on-board sensors and the make and model of the vehicle would also aid developers in recognizing vehicles that may contribute biased data to the VII network. Sensor type and location data, along with vehicle make and model data, would help ensure the general quality of VII data.

A summary of the VII architecture and probe message processes, as currently envisioned, has been presented in preceding sections. It is evident that the way data will flow within the VII infrastructure will have a significant influence on the utility of VII data and product development. Changes in the expected VII framework will alter some of the issues that have been described herein; therefore, it is imperative that product developers monitor the VII deployment process and make a note of architecture and probe message modifications, as these will affect the application and product development process.

Key Points:

The VII concept will enable vehicle-to-vehicle and vehicle-to-infrastructure communication via dedicated short-range radio technology (DSRC-wireless radio communication at 5.9 GHz). This will result in the availability of vehicle data elements that can be used to mitigate the impact weather has on the nation's roadways.

The main factors of the VII program that will influence the use of vehicle data in the improvement and development of road weather products and applications include RSE deployment strategies and probe message processes.

The differences in RSEs spacing in urban versus rural areas, coupled with differences in population, will result in significantly higher quantities of vehicle data across the eastern portion of the U. S. and in and around large cities.

Select components of the probe message processes, such as the probe message hierarchy, vehicle buffer size, and snapshot generation methodology, will affect data quantity, quality, timeliness, and representativeness; however, in urban areas, some of these issues will be overcome through the shear amount of data that will be available.

5. Weather-Related Vehicle Data

PROSPECTIVE DATA ELEMENTS: USES AND ISSUES

The automotive industry is making significant technological advancements in the areas of vehicle environmental sensing and vehicle responsiveness to road conditions. Because of these developments, direct measurements of environmental variables such as temperature and pressure are becoming routine. Other variables presently available on vehicles such as wiper setting, anti-lock brake status, and stability control status, have the potential to address weather-related safety and mobility challenges that motorists experience on a daily basis. It is also expected that continued innovation within the automotive sector will provide opportunities to measure or derive additional atmospheric and road condition parameters.

5.1 Potential Data Elements

The FHWA Road Weather Management Program identified and published a comprehensive list of road weather related variables that have a considerable impact on roads, traffic flow, and operations *(1)*. Improvements in weather and road condition observations and forecasts are needed to minimize the impact of weather on the roadway system. Can vehicle data contribute to the solution?

The first column in Table 5.1 contains a list of the high impact road weather variables noted by the FHWA Road Weather Management Program. The second column lists the corresponding vehicle data elements that have been identified as having the potential to contribute to the diagnosis and prediction of each road weather variable. The final two columns highlight the challenges and issues associated with using the vehicle data and provide additional commentary regarding selected elements. The information supplied in the table assumes that vehicle location (GPS latitude and longitude) and time will be transmitted along with the vehicle data elements noted in the table.

TABLE 5.1 Weather-Related Vehicle Data Elements.

Road Weather Variables	Corresponding Vehicle Data Elements	Challenges and Issues	Comments
Air temperature	- Ambient air temperature - Hours of operation - Elevation	- Multiple sensors for the same parameter possible on vehicle - Sensor placement - Sensor bias	- Data may not be useful at low speeds, so a speed check will be required. Temporal filtering is applied on some vehicles, so data may not be useful for several

		Multiple sensor manufacturers	minutes after startup. The time it takes to reach equilibrium will depend on the difference between the ambient temperature and initial sensor temperature.
Relative humidity	None at present	Humidity measurement is desired, but not presently available	Humidity measurements will likely become more widely available as technology advances Sensor placement and calibration issues will need to be addressed.
Wind speed	Accelerometer data Vehicle speed Heading Rate of change of steering wheel (force required to maintain current heading). Atmospheric pressure	Accelerometer data difficult to use Steering data impacted by more than crosswind (e.g., road grade)	Sensing advances in the automotive industry may provide direct wind measurement capability in the future. Deriving wind speed from other data may not be feasible.
Precipitation (type, rate, start/end times)	Windshield wiper setting Rain sensor Ambient air temperature Vehicle speed Ambient noise level Video	Multiple sensors for the same parameter possible on one vehicle Sensor placement Sensor bias Multiple sensor manufacturers Human factor issues related to wiper usage Impact sensor data not widely available	Wiper use may be related to factors other than precipitation (cleaning windshield, road spray, etc.). Statistical approaches to filter out spurious use will likely be required.
Fog	Fog lights Headlights - Low beam - High beam - Tail lights Adaptive cruise control (ACC) radar Vehicle speed Elevation Relative humidity Video	Human factor issues related to fog light and headlight usage Currently, ACC not widely available ACC not used in urban areas Humidity measurement not presently available	Statistical approaches and data fusion techniques will likely need to be applied to derive fog conditions.
Pavement temperature	Ambient air temperature Sun sensor Pavement temperature	Multiple sensors for the same parameter possible on one vehicle Sensor placement Sensor bias Multiple sensor manufacturers Pavement temperature not widely available	A small number of maintenance vehicles are currently outfitted with pavement temperature sensors, so these data could be used to evaluate its potential. Infrared devices require calibration and the sensor needs to reach equilibrium with the ambient temperature. If the road is covered with debris

			(e.g. snow, ice, leaves), the device will measure the debris temperature and not the pavement temperature.
Pavement condition	Ambient air temperature ABS Traction control Stability control Pavement temperature Brake status Front wheel angle Rate of change of steering wheel Accelerometer data Video	Multiple sensors possible on one vehicle Sensor placement Sensor bias Multiple sensor manufacturers Pavement temperature not widely available Traction control only works up to a specified speed Accelerometer data difficult to use	A significant amount of research will be required to determine the feasibility of deriving pavement condition utilizing vehicle data. Ancillary data will need to be integrated with vehicle data.

The challenges and issues presented in Table 5.1 highlight the need to account for possible differences in the sensors types used by automobile manufacturers, along with variations related to where the sensors are placed and their primary function, as these factors will influence data quality and accuracy. It may also be necessary to develop a comprehensive understanding regarding the way in which vehicle operators interact with and use on-board systems. This information could be used to refine products that are based on vehicle data. Finally, not all vehicle data will be available in the quantities needed to support the development of new applications or impact existing applications; it will be several years before certain variables (e.g. pavement temperature) are widely available on vehicles. These challenges and issues are discussed in further detail in Section 10 of this document.

The following sections provide a more comprehensive look at some of the vehicle data elements presented in Table 5.1.

5.2 Ambient Temperature

Vehicle measurements of outside air temperature are commonplace as this data element is required for the efficient operation of the vehicle emission system. Many vehicle models have multiple temperature sensors. In fact, in many of today's production vehicles, the operator is presented with a digital readout of the current ambient temperature. In some cases, the temperature presented to the operator is from a different sensor than that used for engine performance. Ambient temperatures derived from mobile platforms could be used to enhance weather-related products for the surface transportation industry. However, utilizing these data will not be without its challenges and caveats.

Automobile manufacturers acquire temperature sensors from a variety of original equipment manufacturers (OEMs); therefore, temperature readings from two separate vehicles within close proximity of each other may differ slightly because of the sensing characteristics of the devices. This may also hold true for vehicles of the same make. Moreover, without some type of standard in place for VII probe data, temperature measurements that come from vehicles could be taken from different physical locations on each vehicle. For instance, one automobile manufacturer may provide temperature values associated with the air intake sensor on the vehicle, while another could supply measurements from a sensor mounted behind the radiator grille and in front of the engine compartment, as is the case with the Jeep Grand Cherokee. Some vehicle models (e.g., Honda Pilot) have a temperature sensor in the front bumper. A recent investigation by Mitretek on vehicle-based air temperature measurement accuracy showed that sensor placement has a significant impact on air temperature measurements *(13)*.

Sensor responsiveness to environmental temperature change is also an important factor. An ambient air temperature sensor on a vehicle that has been housed in a garage will take some period to adjust to the outside air temperature once the vehicle exits the garage. The larger the initial temperature difference, the longer the response period. Temperature values displayed to the operator may also be filtered by internal software in an effort to dampen out temperature oscillations and provide a level of continuity more in line with the vehicle operator's expectations. If these values are collected by the vehicle and transmitted to the VII network, some spatial variations in the surface temperature field will be lost.

It has been shown that temperatures retrieved from mobile sensing platforms can also be impacted by both idle time and heavy traffic *(13)*. The measured ambient air temperature can exhibit a warm bias under these conditions; therefore, knowing how long the vehicle has been in operation and the traffic conditions in which the vehicle is operating at the time the measurement is taken will be essential to making effective use of these data.

5.3 Relative Humidity (Dew Point)

Knowing the relative humidity at scales that VII would enable will have considerable implications on the diagnosis and prediction of several high impact weather and road conditions. There is little doubt that relative humidity data in sufficient quantities would almost instantly result in improvements in the analysis and forecast of precipitation and fog. However, this variable is not currently available on the majority of production vehicles. Notable achievements in the automotive industry regarding the measurement of relative humidity are related to measurements taken on the inside of the front windshield. Data from humidity sensors on the inside of a windshield are being used to anticipate the formation of moisture on the windshield; as a result, the climate control system can be automatically activated and adjusted to mitigate windshield fogging. Humidity measurements of this type will not directly benefit the development of weather-related applications, but advancements in on-board cabin relative humidity measurements may lead to the production of low cost exterior devices that assess and monitor atmospheric moisture content in support of automotive applications such as engine efficiency applications.

Knowledge about the water vapor content of the atmosphere, whether it is derived from dew point or relative humidity measurements, is critical, as water vapor is an atmospheric state variable that directly influences the formation of clouds, precipitation, and fog. Water vapor is one of the most variable measurements in space and time. Slight changes in its value over small temporal or spatial scales can have a large impact on weather and road conditions. Improving the measurement of boundary layer moisture is a very high priority of the atmospheric science community. Because the atmosphere is very sensitive to water vapor, sensing systems must be very accurate. This poses a challenge to the automotive industry because accurate water vapor sensors are more expensive than temperature sensors. The benefit of having accurate water vapor measurements is high, so an investment in research in this area would be worthwhile.

Because the price of water vapor sensors is high, it may not be practical in the short term to expect vehicle manufacturers to instrument vehicles with these sensors. Another possible approach would be to instrument a subset of vehicles with water vapor sensors. Vehicle fleets that have broad coverage on a daily basis would be good candidates for these sensors. Fleets that have broad coverage on a daily basis could include vehicle fleets that deliver mail or packages, for example. State maintenance or emergency vehicles may also be candidates for additional atmospheric sensors.

5.4 Wiper State

Wiper state would be another extensively used variable because it is widely available, and can provide information about the state of the atmosphere (precipitation) and roadway (wet or dry).

A key factor in using information linked to wiper state is understanding how different vehicle operators interface with and use the wiper settings under disparate conditions. Research conducted by the University of Michigan suggests that middle-aged drivers used the wiper system the most, while older drivers reduced their speed and increased their headway time margin (time to the preceding vehicle) once the wipers are on *(14)*. Further research is necessary in order to fully document how wipers are used during adverse weather conditions. Due to privacy concerns, specific information regarding the driver will not be available through VII, but it may be essential for application and product developers to account for variations in the way populations use windshield wipers.

From an application development standpoint, wiper state will be useful in determining where precipitation is occurring, as it would provide a binary indication (yes or no) of the presence of rain or snow. However, it is likely that wiper state data will need to be used in conjunction with ancillary data to identify areas of precipitation. Windshield wipers are not only used during precipitating conditions, but they are employed when roadways are wet and no precipitation is occurring. Driving in moderate to heavy traffic conditions on wet roadways sometimes requires the use of low or intermittent wiper settings because of the existence of roadway spray. These conditions generally occur after the passage of rain/snow or in between showers. Operators also use wipers when washing the windshield. If used improperly, wiper state could lead to a misdiagnosis of precipitation occurrence. Because most automobile crashes occur under wet pavement conditions, the characterization of roadways (wet or dry) using wiper state data will also be valuable, but it too will likely require supplemental data.

5.5 Rain Sensor

Some of the difficulties associated with the use of wiper state data would be alleviated to some extent by the proliferation of rain sensors. Rain sensors generally operate on the principle that the accumulation of water on the outside of a windshield will disrupt an infrared beam of light that is emitted by the sensor, which is mounted on the inside of the windshield. The magnitude of this disruption can be correlated to the amount of water on the windshield. Information from these sensors is used to control the operation of windshield wipers, including the speed and interval of the wipers. Rain sensors would provide accurate, objective data related to wiper usage. Nonetheless, the sensors will not solve the problem of discriminating between precipitation and road spray; the sensor functions solely on the basis of water on the windshield, and does not account for the source of the water.

It is also not clear how well rain sensors function when it is snowing or if they will falsely report rain when ice and snow melt off the windshield. Additionally, rain sensors may falsely indicate the absence of precipitation when vehicles drive under bridges or enter tunnels, even though heavy precipitation may be occurring. In these situations, the amount of water on a vehicle's windshield would be considerably reduced, and data from the sensor would suggest a lack of precipitation at that location. Furthermore, these data would turn off the wipers or significantly decrease wiper speed.

5.6 Lights (Fog and Headlights[4])

As with windshield wipers, information associated with vehicles' outside lighting systems would be broadly accessible through VII. It is anticipated that information regarding light status would be used to infer conditions related to the current state of the atmosphere (e.g. rain, snow, fog, darkness, etc.). Again, the human factors aspect is significant with respect to how drivers use headlights and fog lights. Although all drivers are taught to turn on their lights when precipitation is occurring, visibility drops significantly, or near sunset, not all drivers adhere to these standards. Even drivers that do their best to follow these guidelines do not operate headlights or fog lights in a consistent manner. Increasingly, vehicles are equipped with devices (e.g. sun and rain sensors) that are capable of operating the lights without the assistance of the driver which would minimize the subjective nature of headlight and fog light operation. Utilizing headlights or fog lights to derive information about the environment will require a rich set of vehicle observations as well as ancillary data (weather radar, satellite, surface observations, etc.).

5.7 Accelerometer

Vehicle acceleration, braking and turning results in forces that can be sensed and measured by an accelerometer. One of the most notable uses of accelerometer data is to deploy air bags when a vehicle undergoes a rapid

[4] Assumes that taillights are active when headlight switch is in the on position. In this document, running lights are not considered, as they are not likely to support road weather applications.

deceleration. These data can also be used to initiate other automotive systems such as stability control. A three-axis accelerometer can provide information regarding forces along the longitudinal, lateral and vertical axes. In terms of basing weather applications and products on these data, it will be necessary to use accelerometer data in conjunction with other vehicle data elements. Additionally, a significant amount of research and development will be required to make effective use of these data, and product developers will need to work closely with OEMs to gain an adequate understanding of the issues related to accelerometer data.

As indicated in Table 5.1, it may be possible that data from accelerometers could be used to derive information about wind and road conditions. During high wind events, accelerometer data, along with data associated with steering wheel inputs and nearby surface meteorological stations, could be used to infer areas of high winds blowing perpendicular to a roadway. Many drivers have experienced conditions where their vehicle was subjected to high winds, and as a result, sudden vehicle accelerations (longitudinal and/or lateral) occur, which require abrupt steering inputs from the driver or moderate steering force to maintain control and the desired heading. It is very unlikely that currently available vehicle data can be used to accurately derive wind speed and direction; however, providing high wind alerts to drivers, especially operators of high profile vehicles, would be extremely valuable.

The discussion contained in the following section supplies additional background on how accelerometer data will benefit VII-enabled analyses.

5.8 ABS, Traction Control and Stability Control

The Anti-lock Braking System, or ABS, was introduced on production vehicles approximately 20 years ago. During deceleration, ABS prevents the wheels of a vehicle from locking up in an effort to maximize traction. The advent of ABS was followed by traction control, which also works to maximize traction during acceleration by minimizing wheel spin. However, traction control systems only function at low vehicle operating speeds. In recent years, a growing number of production vehicles have come with stability control. Stability control uses a combination of throttle and braking action to control the lateral movement (yaw) of the front and/or back of a vehicle in an attempt to keep the vehicle from getting into an uncontrolled skid.

Each of these systems is designed to monitor wheel events linked to the pavement/tire interface. By making appropriate adjustments to other onboard systems (e.g. throttle, braking, etc) the greatest amount of traction possible is achieved. Wheel lock, spin, and sideslip by and large are more likely to occur during adverse road conditions when surface friction is low. Thus, information gathered through VII concerning the actuation of these systems would be able to aid in diagnosing slippery road conditions (e.g. wet, snow covered, icy).

To get an accurate assessment of road conditions using ABS, traction control, and stability control data, it will be necessary to gather supplementary data related to the vehicle's motion. It is possible to record an ABS event when roadways are dry. For instance, an ABS event may occur on a dry roadway when a driver is required to come to an abrupt stop to avoid an accident. During this type of scenario, a significant amount of brake pressure (100% brake boost) is usually applied and the deceleration recorded by an accelerometer is relatively high. In a situation where an intersection is snow-covered and a driver is required to stop for a red signal light, an ABS event is less likely to be accompanied by strong braking and a sharp deceleration. Of course, a vehicle stopping on a dirt or gravel road may generate similar sensor reports; therefore, information on the road surface may be required to differentiate poor road conditions.

5.9 Sun Sensor

It has been long recognized that solar radiation (insolation) is a critical component in forecasting road temperature. Automotive innovation has led to the increased use of sun sensors to automatically control the heating, venting, and air condition systems on vehicles by detecting the strength of sunlight entering the cabin of the vehicle. Data obtained from these sensors through VII will lead to a more accurate assessment of sky conditions, which would translate into more accurate road temperature forecasts. Presently, sun sensors are available on higher end automobiles, so it may be some years before there is enough data available from these sensors to improve road temperature predictions.

5.10 Driver Assist Systems

A considerable amount of research is being conducted to develop systems that will assist vehicle operators in the identification and avoidance of driving hazards. These systems include the use of radar and video technology. An example of this can be seen in the emergence of Adaptive Cruise Control (ACC) systems, which utilize millimeter-wave radar (76-77

GHz) to detect vehicles in front of the host vehicle and adjust the host vehicle's speed accordingly to maintain a safe driving gap. Although radar technology used in driver assist systems is not largely impacted by adverse weather by design, it may be possible to use these data to detect some weather-related driving hazards (e.g. fog).

Millimeter-wave (MMW) radar systems are used in a wide range of applications today including adaptive cruise control, automobile collision warning, missile guidance, speed measurement, and clear air turbulence. The characteristics of the radar vary greatly depending on the use. More expensive millimeter-wave radars are pulsed and may include a Doppler capability. Less expensive radars utilize continuous wave (CW) technology including frequency modulated continuous wave technology, which has an excellent ability to measure target range.

The portion of the electromagnetic spectrum that comprises the MMW region ranges from 30 to 300 GHz or wavelengths of 10 mm to 1 mm (15). Atmospheric propagation effects play a large role in the design and utilization of radar applications operating in the MMW region. Propogation effects include absorption, attenuation, backscatter, phase variation, polarization, ducting, arrival angle variations, and surface phenomena *(16)*.

The attenuation[5] of MMW at sea level and 4 km altitude is displayed in Figure 5.1. There are several frequencies that exhibit minimal atmospheric attenuation (35, 95, 140, and 220 GHz); however, other frequencies are significantly impacted by oxygen and water vapor. Figure 5.2 displays the impact of rain and fog on the propagation of MMW energy. These data indicate that losses due to rain are greater than fog. This characteristic is supported by a study conducted by the University of California. The investigation found that precipitation in the form of rain and wet snow had the largest attenuation effects when compared to dry snow and fog, which had much smaller effects *(16)*. Although driver assist systems that use MMW radar have been designed to mitigate the impact of adverse weather, it is possible that MMW data could contribute to the diagnosis of hazardous weather, especially at the 24 GHz frequency, which has been targeted for short-range driver assist applications such as blind spot detection applications, which aids in the detection of objects in vital zones around the vehicle.

[5] A decrease in signal strength from one point to another resulting from absorption and scattering *(17)*.

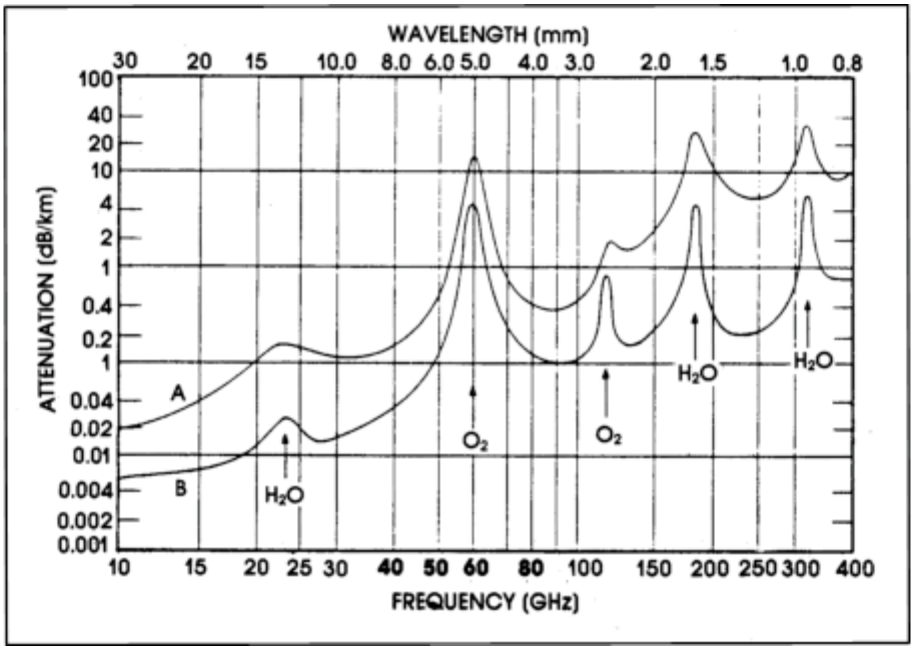

FIGURE 5.1. Atmospheric absorption (average) of millimeter-waves at sea level (line A, Temperature=20°C, Pressure=1013.25 mb, Water Vapor Density= 7.5 g/m^3) and altitude of 4 kilometers (line B, Temperature=0°C, Water Vapor Density= 1 g/m^3) *(15)*.

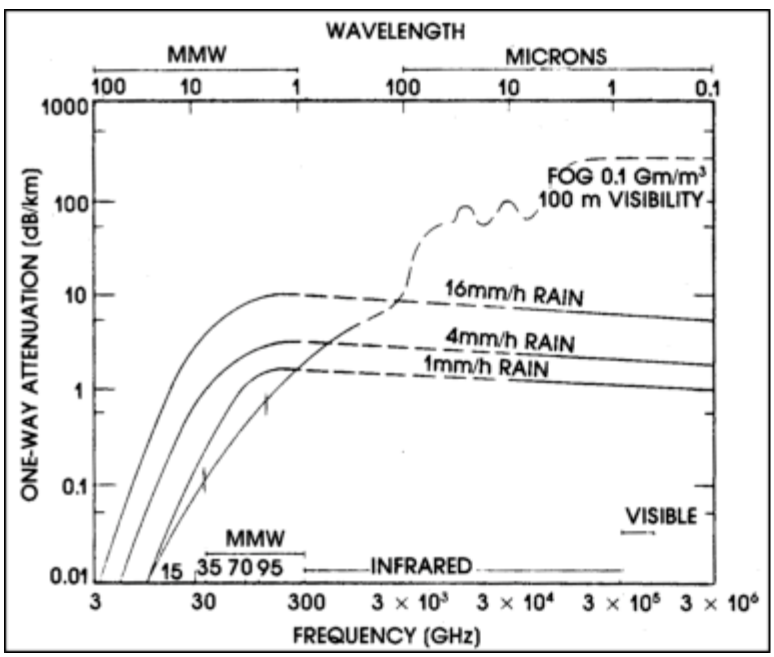

FIGURE 5.2. Impact of rain and fog *(15)*.

Video data would act as a surrogate for radar data in the detection of adverse weather. As advancements associated with driver assist video technology are realized, timely and accurate assessment of road weather hazards will be made possible through pattern recognition techniques.

Key Points:

Vehicles are currently capable of contributing data that would lead to improvements in road weather applications and products. Presently, weather-related vehicle data elements range from direct measurements of environmental conditions (e.g. temperature) to indirect indications of road conditions (e.g. ABS). Further advancements in the automotive industry will likely result in additional data that could help facilitate subsequent advances in the timeliness and accuracy of road weather products. Due to issues such as variations in sensor type, sensor placement, and principal function, there will be a need to develop a comprehensive understanding of each weather-related vehicle data element. This understanding would ensure appropriate and effective use of VII-enabled data.

6. Case Studies

INVESTIGATING ACTUAL WEATHER-RELATED VEHICLE DATA ELEMENTS

The efficacy of VII-enabled data is illustrated in Figures 6.1 and 6.2. Figure 6.1 displays data from a DaimlerChrysler vehicle operating north of the Detroit downtown area on 16 February 2006. Included in the figure are radar data (base reflectivity) from the Detroit Doppler weather radar valid closest to the time of the vehicle data. Data were available from the vehicle at one-minute intervals, while base reflectivity scans were available on six-minute intervals. The radar data show reflectivity or echo intensity measured in decibels (dBZ), which generally correlates with precipitation rate. Cooler colors indicate lower reflectivity and warmer coolers indicate higher reflectivity. Vehicle data elements include information on wiper state: 0 is off, 13 is low, 14 is high, and 1 through 6 are intermittent settings. Barometric pressure in inches of Mercury (inches Hg) and air temperature in degrees Fahrenheit (^{o}F) are also supplied.

The Automated Surface Observing System (ASOS) located at the Detroit City Airport (DET) reported light rain and misty conditions throughout much of the day on 16 February, with some thunderstorms during the afternoon and evening hours. Temperatures ranged from about 34^{o}F (1^{o}C) in the morning to a high of roughly 55^{o}F (13^{o}C) in the afternoon and evening. Station pressure ranged from approximately 28.90 to 29.40 inches Hg during this time.

Figure 6.1A shows the vehicle driving shortly after noon (17:12Z) on 16 February. At this time, the wiper state is zero, which denotes that the wipers are not in operation. This is consistent with radar reflectivity returns in the area; there are no reported radar echoes in the immediate vicinity of the vehicle. An area of light to moderate reflectivity does exist to the south of the vehicle's location. These echoes are moving to the northeast. An air temperature of 35.6^{o}F (2^{o}C) is reported by the vehicle. This is well correlated with the 33.8^{o}F (1^{o}C) atmospheric temperature reported by the Detroit ASOS (approximately 12 miles southeast of the vehicle's location) station about half an hour earlier. This difference is reasonable, as nearby convection and/or frontal boundary location may be influencing the readings. By 17:58Z (Figure 6.1B), the radar echoes have moved into the vehicle's area. Data from the vehicle indicates that the wipers are on low. Temperature and pressure readings have increased slightly. Figure 6.1C and 6.1D capture the vehicle moving to the northwest along Interstate 75 at 23:25Z and 23:49Z, respectively. In Figure 6.1C, the wipers are on, but the driver is utilizing an intermittent setting. This setting could be the result of very light precipitation in the area, spray from the roadway, or a combination of both. The wiper setting changed to high by 23:49Z, which correlates with the more intense echoes observed by the radar. According to the vehicle data, temperatures have risen between 14-18^{o}F (8-10^{o}C) from those reported some six hours earlier. Again, this is consistent with ASOS data, as was the reduction in pressure reported by the vehicle. This case is promising; it indicates that the vehicle data are consistent with the nearby official surface observations and radar data.

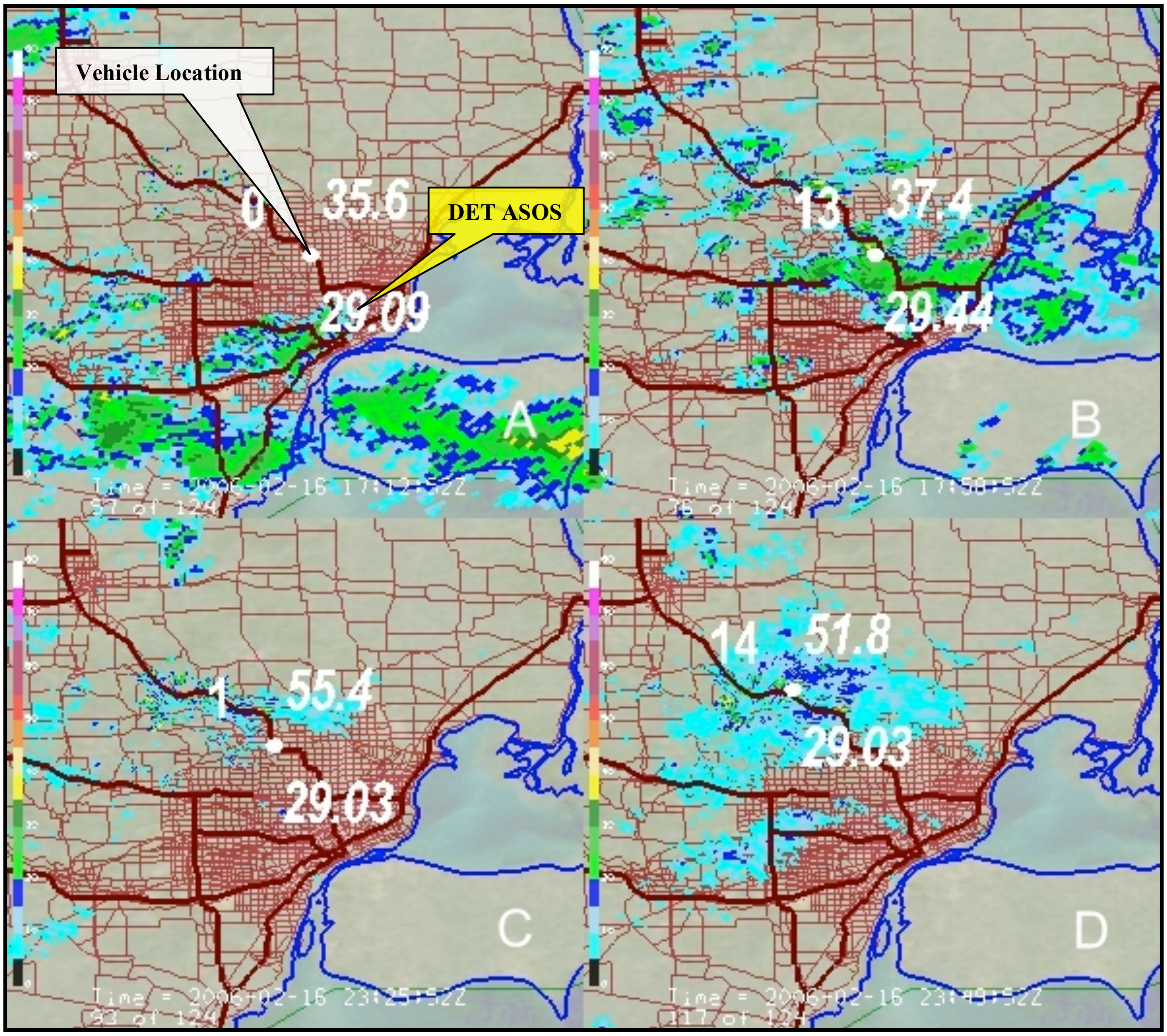

FIGURE 6.1. Vehicle data valid at 17:12Z (A), 17:58Z (B), 23:25Z (C), and 23:49Z (D) on 16 February 2006 overlaid with WSR-88D radar data. Vehicle data include vehicle position (white circle), wiper state (to the upper left of vehicle location), atmospheric temperature (^{o}F) (upper right), and barometric pressure (inches Hg) (lower right). Vehicle data courtesy of DaimlerChrysler. [6]

On 25 May 2006, thunderstorms moved through the Detroit area and resulted in multiple outflow boundaries. Outflow boundaries are generated when colder, upper-level air associated with a thunderstorm(s) descends to the surface and spreads out horizontally forming a boundary between the colder, denser air and the surrounding environment. Outflow boundaries may persist for more than a day and serve as initiation points for new thunderstorms. An outflow boundary can result in density discontinuities across the boundary, and the convergence along the leading edge of the boundary can result in blowing dust,

[6] The Integrated Data Viewer from Unidata (www.unidata.ucar.edu) was used in the creation of Figures 6.1 and 6.2.

clouds and precipitation. Selected features of the 25 May outflow event were captured by DaimlerChrysler vehicles operating in the area. Data from one of the vehicles is displayed in Figure 6.2. The data elements are identical to those described previously (i.e. wiper state, temperature, and pressure).

At approximately 21:56Z (Figure 6.2A), the DaimlerChrysler vehicle begins to head to the south. The windshield wipers are off, the air temperature is 82.4^{o}F (28^{o}C), and the pressure is 28.38 inches Hg. The location of an outflow boundary generated by a strong thunderstorm located south of Detroit is identified by the white arrow. As the vehicle progresses southward, there is an increase in reported air temperature (Figure 6.2B). A secondary outflow boundary linked to storms off to the west can also be seen in the radar data. Once the vehicle crosses the eastern portion of the primary outflow boundary, the vehicle temperature decreases significantly and the pressure increases (Figure 6.2C and D). These characteristics are consistent with the passage of outflow boundaries. There is good agreement between radar data and wiper state, which remains unchanged throughout the event. Furthermore, a good correlation between vehicle data and surrounding surface observations (not shown) also exists.

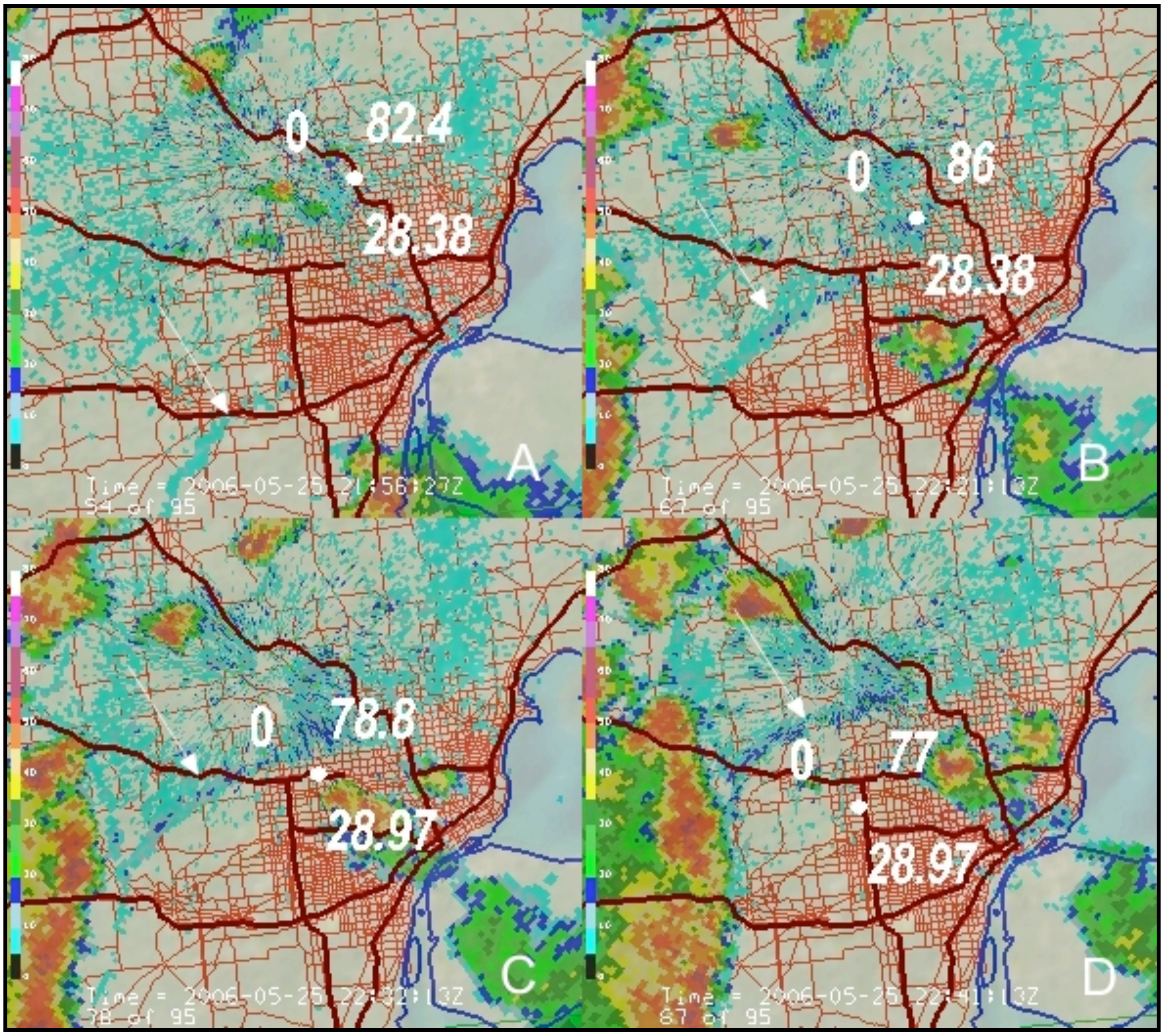

FIGURE 6.2. As in Figure 6.1, except valid times are 21:56Z (A), 22:21Z (B), 22:32Z (C), and 22:41Z (D) on 25 May 2006. Arrow denotes the location of outflow boundary.

Both of these cases demonstrate the benefit of vehicle data in the diagnosis of atmospheric conditions. It is also readily apparent that the proliferation of VII-enabled data would result in information on spatial and temporal scales that would support advances in the analysis and prediction of weather and road condition hazards. For example, in the case of thunderstorm generated outflow boundaries, an adequate number of vehicles would not only aid in identifying the location of the outflow boundary, but would permit additional characterization of the outflow boundary (e.g. scale, structure, etc.). These data can be used to initialize high-resolution numerical weather models, which presently have difficulty analyzing and predicting small-scale structures such as these because there is currently a lack of surface observations on these small-scales.

Weather models today can be run operationally over small domains (620 mi by 620 mi [~1000 km by 1000 km]) with horizontal grid spacing as low at 1/2 miles (~1 km). As the grid spacing of weather models decreases the need for high-resolution observations increases as these data are required to initialize and validate the models. As is evident from the cases presented herein, VII-enabled data will help address the need for more observations.

Key Points:

Case studies that compared vehicle data elements to conventional weather datasets demonstrate the efficacy of mobile data, as a good correlation existed between vehicle data elements (e.g. wiper state, temperature, and pressure) and standard weather measurements (e.g., radar and surface observations). When used in conjunction with ancillary data, vehicle data enabled by VII will result in a number of road weather product improvements. These improvements will include the ability to provide more accurate, timely analyses and forecasts of road weather hazards.

7. Potential VII Products and Applications

WEATHER AND ROAD CONDITION IMPROVEMENTS ENABLED BY VII

In this section, weather and road condition product concepts enabled by vehicle data and/or improvements in weather and road condition products due to the utilization of vehicle data are presented. The examples presented herein were selected because it was felt that they were particularly relevant to the surface transportation community. Surface transportation stakeholder categories that will benefit from weather and road condition products enhanced with vehicle data include, but are not limited to:

- Traffic management
- Incident management
- Maintenance (winter and non-winter)
- Travelers

- Emergency management

The general assumption for this section is that the vehicle data are valid, that is, they have sufficient quality to be utilized in the product concepts described herein. Ideas about the type of methods and techniques that may be required to develop these product concepts are discussed in Section 9.

7.1 Weather Product Improvements Enabled by VII

Several examples of weather products that will be improved with vehicle data are presented in this section. The examples are not exhaustive and only provide a sampling of what will be possible with these new datasets. The product examples include both improvements in the diagnoses of current weather conditions and in weather prediction. The primary potential contribution of vehicle data will be its ability to help characterize the lowest levels of the atmospheric boundary layer as well as pavement conditions.

Weather improvements that will be enabled with vehicle data include, but are not limited to:

- Reducing radar anomalous propagation (AP)
- Improved identification of virga (precipitation not reaching the ground)
- Improved identification of precipitation type
- Improved identification of foggy regions
- Improved characterization of surface conditions for weather models
- Improved weather analysis and prediction in complex terrain
- Improved air quality monitoring and prediction
- Improved diagnosis of boundary layer water vapor

7.1.1 Reducing Radar Anomalous Propagation (AP)

Doppler weather radar data are used widely for many weather applications and products throughout the country. The NWS and DOD operate 158 NEXRAD Doppler weather radars throughout the country. Several sophisticated radar data quality algorithms have been implemented to reduce artifacts such as ground clutter, point targets, and anomalous propagation, but there are still times when data quality suffers from contamination (*18, 19*).

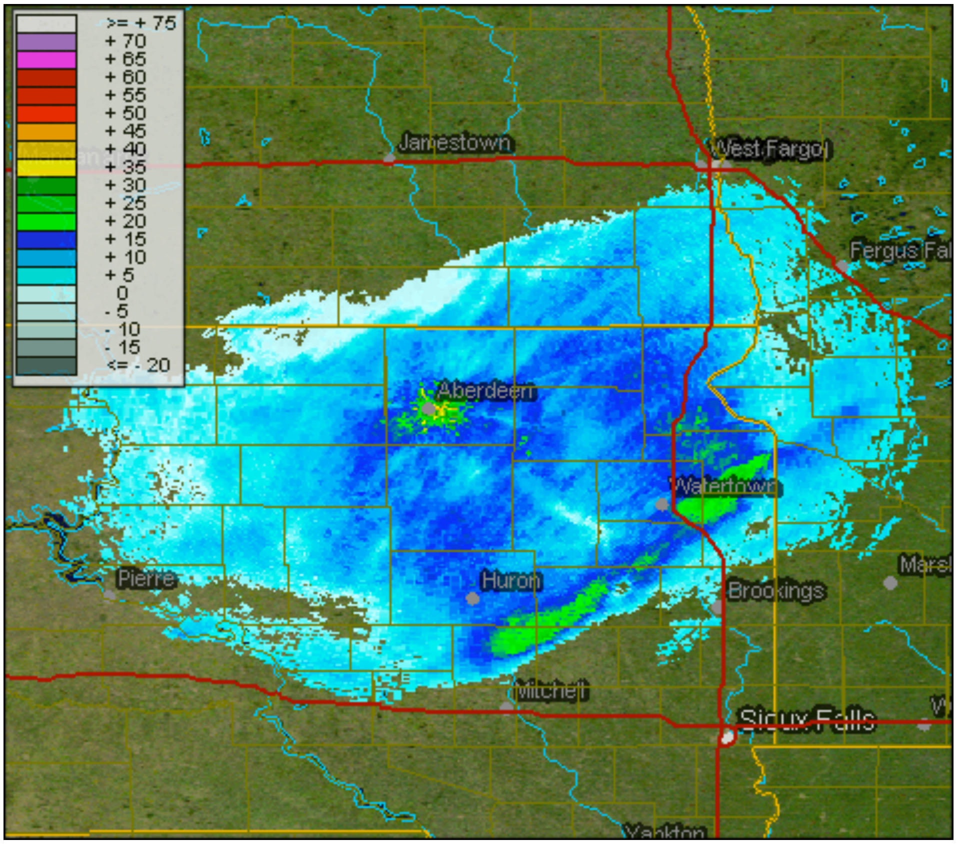

FIGURE 7.1. Doppler weather radar mosaic showing intensity (reflectivity) at Aberdeen, South Dakota on 15 March 2002 at 02:19 UTC. The image illustrates the impact of anomalous propagation (AP) on data quality.[7] Although echoes are displayed in the image, no precipitation was occurring at the ground. None of the echoes displayed are precipitation.

Figure 7.1 is a radar intensity image from Aberdeen, South Dakota from 15 March 2002. Although the image suggests that light precipitation is falling in central South Dakota, no precipitation was reported. The false return was primarily caused by anomalous propagation (AP), whereby the radar beam was bent toward the ground due to a temperature inversion or water vapor discontinuity in the lower atmosphere. Without widespread surface observations, it is often difficult to confirm whether the radar return is real or an artifact. All users of weather radar data are affected in these situations, as it is difficult to determine if the precipitation is real. DOT winter maintenance personnel, who routinely use radar data to guide tactical decision-making, take appropriately conservative measures to begin winter maintenance operations when precipitation is anticipated. If the radar information turns out to be an artifact, the resources used to begin snow and ice control operations are

[7] Image created using the Java NEXRAD Viewer from the National Climatic Data Center.

wasted. Anomalous propagation is not rare and often occurs after precipitation, on clear nights, and after the passage of shallow cold fronts when temperature inversions and/or atmospheric water vapor discontinuities are present.

One of the easiest ways to determine if AP is occurring is to analyze other weather observations to see if there is any corroborating evidence for precipitation. Surface observations and satellite imagery are often used by trained meteorologists and sophisticated algorithms to identify, suppress and/or remove AP from radar data. One limitation of the surface observation network is the low density of observations, particularly when compared to the spatial resolution of radar data samples, which is approximately 1 km (0.62 miles).

> **VII Contribution**: Data from vehicles would help determine if precipitation is occurring in the area in question. The density of vehicle observations will surpass the density of traditional surface observations by several orders of magnitude providing a data rich environment. A direct measurement of precipitation (yes/no) from a vehicle based precipitation sensor would be the best data element to use for this application, but an indirect indication of precipitation from windshield wiper settings could also be used to diagnose the presence of precipitation. Temperature data from vehicles could be used as supplementary input to AP suppression algorithms that are currently applied to radar data by commercial weather vendors.

> **Challenges:** The primary challenge associated with using vehicle data for this application is the uncertainty of how wiper systems are used as was noted in section 5.4. Statistical processing can be used to remove outliers such as when people are using wipers to clean the windshield. The more challenging problem is the use of wipers by a large population of vehicles to address splash-back from wet roads when there is no precipitation. This scenario could lead to AP not being suppressed when it should be because the algorithm may indicate that precipitation is occurring or is likely to be occurring. The majority of time, however, AP will occur in clear conditions, and in these circumstances the use of vehicle data will be more straightforward and have a positive impact.

Vehicle Data Applied to Reducing Radar Anomalous Propagation		
Relevant Data Elements	**Processing Summary**	**Primary Challenges**
Time	Precipitation sensor and/or wiper setting could be used along with other	Identifying occasions when wipers are used or
GPS Location		

Precipitation Sensor Windshield Wipers (front) On/Off Outside Air Temperature	meteorological datasets to diagnose the presence of precipitation. The vehicle data will be one of many inputs to AP suppressing algorithms.	precipitation sensors are responding to splash-back when no precipitation is occurring. If a rain sensor is used as the primary data source, one has to be aware that it will not likely record frozen precipitation.

7.1.2 Improved Identification of Virga

Doppler radars use specific volume scan strategies in an attempt to sense precipitation. The most common strategy, volume coverage pattern 21 (VCP-21), is where the radar makes nine elevation scans from 0.50^{o} to 19.5^{o} every six minutes. As the radar transmits energy at each of these elevations or beam angles, it is also rotating 360 degrees. In some situations, the radar may be accurately sensing precipitation, but the precipitation may not be reaching the ground. Precipitation that does not reach the ground is called virga. When the lower atmosphere is dry, the likelihood of virga increases.

Users of weather radar data are very aware that occasionally the radar data may indicate widespread precipitation when no precipitation is reaching the ground. This situation can last for hours and it is difficult for users to determine if and when the precipitation will reach the ground. This is not a radar artifact as the radar is correctly measuring precipitation. Transportation maintenance (winter and non-winter) and traffic management personnel require accurate radar products to plan operations. Travelers also need accurate surface precipitation information.

> **VII Contribution:** The most direct method of determining whether the precipitation is reaching the ground is to look at surface observations; however, the density of surface observations of precipitation is very low, particularly in remote areas. Vehicle data would be used to supplement standard precipitation observations. Windshield wiper and rain sensor data would be used to determine if precipitation is reaching the ground and that information could be used to adjust and calibrate radar products. This product concept is demonstrated in Figure 7.2 where a radar image from the Front Range NEXRAD (near Denver, Colorado), shows light precipitation northeast of Denver along the I-76 corridor. There are few surface observation stations in the region, so transportation system users would not be able to determine if the measured precipitation was reaching the ground. If vehicle measured wiper setting and/or rain sensor data were available, these data would be used to diagnose the actual presence of precipitation at the ground.

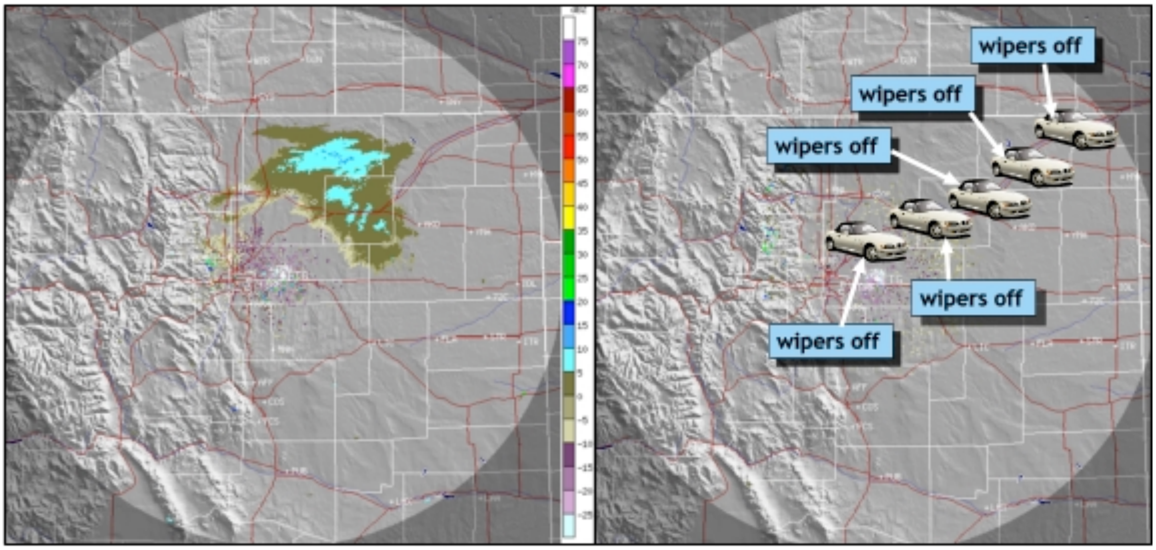

FIGURE 7.2. Denver NEXRAD radar image from 9 February 2006 showing virga in northeast Colorado (left image). Conceptual illustration (right image) of an improved surface precipitation product showing no precipitation at the ground based on an algorithm that correct the product by taking advantage of vehicle data from vehicles traveling along I-76.

> **Challenges:** The primary challenge associated with using vehicle data for this application is the uncertainty of how wiper systems are used. Statistical processing can be used to remove outliers such as people using wipers to clean the windshield. The more challenging problem is the use of wipers by a large population of vehicles to address splash-back from wet roads when there is no precipitation. This scenario could lead to false positive reports of precipitation and the precipitation product not being corrected when it should be.

Vehicle Data Applied to Improving the Identification of Virga

Relevant Data Elements	Processing Summary	Primary Challenges
Time GPS Location Precipitation Sensor Windshield Wipers (front) On/Off	Precipitation sensor and/or wiper setting would be used along with other meteorological datasets to diagnose the presence of precipitation. The vehicle data will be used to adjust/calibrate the radar data and products.	Identifying occasions when wipers are used or precipitation sensors are responding to splash-back when no precipitation is occurring. If a rain sensor is used as the primary data source one has to be aware that it will not likely record frozen precipitation.

7.1.3 Diagnosis of Precipitation Type

Transportation professionals frequently cite precipitation type as one of the most important weather factors influencing the transportation system as it impacts mobility and safety. Identification of the rain/snow boundary is a challenge for the meteorological community as subtle changes in the atmospheric boundary layer such as air temperature, humidity, and precipitation rate can have a dramatic affect on precipitation type.

The Doppler radar technologies utilized throughout the country today (e.g., NEXRAD, media radars, and Terminal Doppler Weather Radars) do not have the ability to directly measure precipitation type. Radar intensity is based primarily on the size of precipitation particles and secondarily on the number of precipitation particles. Advanced weather radars with dual-polarization capability do have the ability to diagnose precipitation type by measuring the shape of the precipitation particles, but it will be many years (approximately 5-10 years) before this new technology is implemented broadly across the nation. In the meantime, precipitation type will continue to be diagnosed using a combination of observational data and weather model analyses.

The lack of a dense surface observation network makes it difficult to generate a high-resolution precipitation type product. Today, precipitation type products often include a broad area designated as *mixed* precipitation, which generally means that the precipitation may be liquid (rain) or frozen (snow, ice pellets, or freezing rain). The lack of certainty about the precipitation type impacts transportation operations, particularly winter maintenance, as personnel must assume the worst-case scenario and mobilize snow and ice control assets.

The addition of dual-polarization technology on the nation's WSR-88D network and the addition of new low-power local radars with dual-polarization, such as the Collaborative Adaptive Sensing of the Atmosphere (CASA) radar, will significantly improve the ability to diagnose precipitation type. Even with those new technologies in place, precipitation type observations taken from vehicles will be beneficial as these observations will be used as verification data to calibrate the radar algorithms and as input to more sophisticated precipitation type algorithms that combine multiple datasets including radar, surface observation, and model analyses and forecasts.

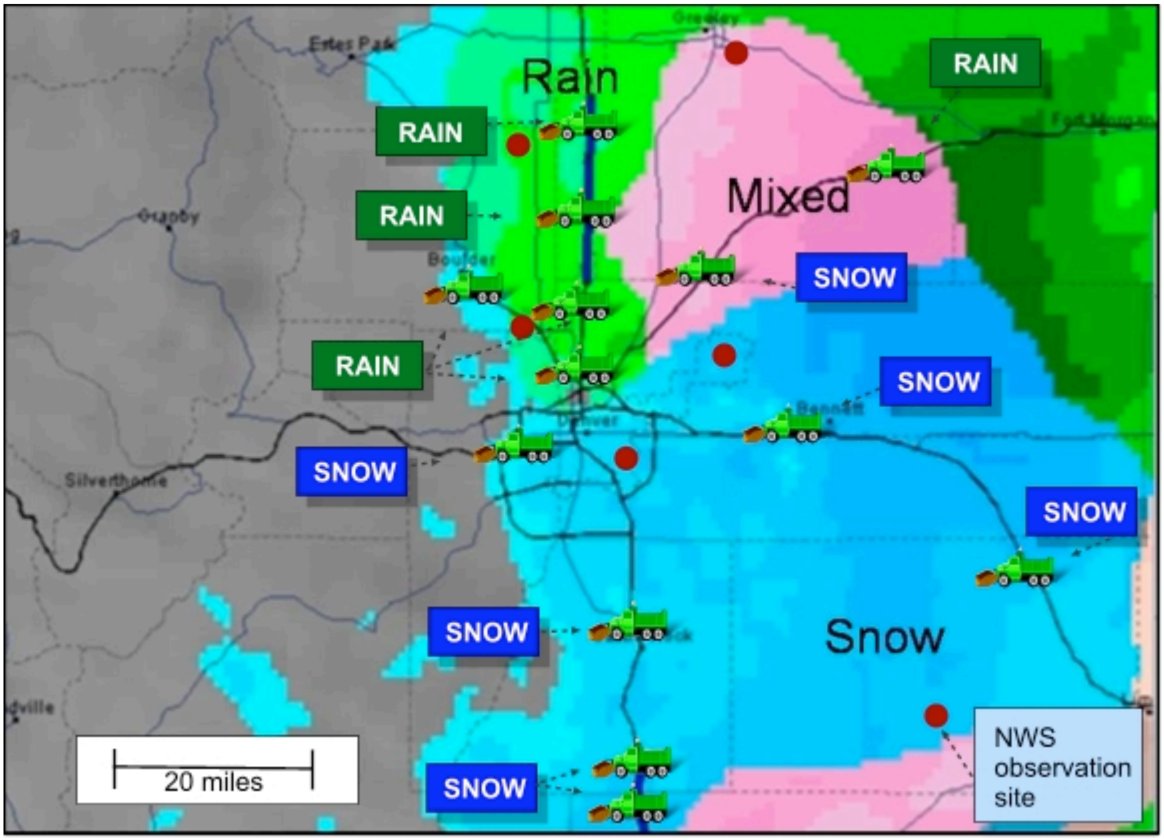

FIGURE 7.3. Illustration of a precipitation type product near Denver, Colorado from October 2005 overlaid with conceptual observations taken by winter maintenance vehicle drivers. The vehicle observations, which would supplement the standard surface observations, could be used by precipitation type diagnosis algorithms to improve the temporal and spatial resolution of the product. The locations of NWS surface observations stations are shown as circles.

VII Contribution: Vehicle data would be used to improve the diagnoses of precipitation type. Surface air temperature is one of the primary factors in the diagnosis of precipitation type, so air temperature data from vehicles would supplement traditional surface observations. The inclusion of vehicle based air temperature observations in precipitation type diagnosis algorithms would improve the spatial and temporal resolution of precipitation type products.

In addition to vehicle measured air temperature observations, direct observations of precipitation type as determined by drivers of winter maintenance vehicles would be beneficial. On-board technologies now exist that allow drivers to input and transmit both sensor-measured and driver-observed weather and road condition information to a central DOT information system. The driver-based observations would be treated as high quality surface observations and be utilized by algorithms designed to diagnose precipitation type over a broad region.

This product concept is illustrated in Figure 7.3 for a winter storm event that occurred in Denver, Colorado in October 2005. The precipitation type product shown in Figure 7.3 is based on a combination of standard NWS surface observations (at airports near Denver), Doppler weather radar, and weather model analyses. The location of NWS surface observation sites is shown as small circles and in this example, six surface observation sites (airports) were utilized in the precipitation type algorithm. The distance between surface observations range from approximately 20 miles to more than 50 miles. Outside of the Denver area, the lack of surface observations significantly affected the quality of the precipitation product since surface observations carry significant weight in the precipitation type algorithm.

If precipitation type information from vehicles were available, the temporal and spatial resolution of the product would be improved as the number and distribution of observations would exceed the fixed observational sites. Anecdotal feedback obtained from transportation authority personnel near Denver for this event suggested that the actual precipitation type did not always match the reported precipitation type particularly for locations away from the NWS reporting sites. This discrepancy is illustrated conceptually in Figure 7.3 where several vehicle-based observations disagree with the analyzed precipitation type.

Challenges: The primary vehicle data elements that would be utilized in this case are air temperature and manual observations of precipitation type. Because precipitation type is highly sensitive to surface air temperature, the quality of the vehicle air temperature would need to be very high. Just a one degree error in a surface air temperature measurement could result in an error in the diagnosed precipitation type. It is very likely that a statistical approach would need to be utilized to ensure that the vehicle based air temperatures represent the predominant condition in the region of interest.

One would expect that human observations of precipitation type from vehicles would be quite accurate; however, this may not always be the case. If this capability were realized, it would be very important that the observations be recorded at the right place and time and not displaced. For example, a driver may observe snow, but not enter the observation into the on-board system until some time later, which could result in the wrong time and location information being tagged to the observation. It is likely that statistical processing would mitigate these issues, but they may still present a concern.

Vehicle Data Applied to Diagnosing Precipitation Type		
Relevant Data Elements	**Processing Summary**	**Primary Challenges**
Time GPS Location Outside Air Temperature Manual observation of precipitation type taken by transportation operations personnel	The outside air temperature would be used to supplement standard surface air temperature observations from fixed locations (e.g., NWS and RWIS sites) and be utilized in precipitation type diagnosis algorithms. Manual observations of precipitation type taken by transportation operations personnel would be utilized by precipitation type diagnosis algorithms.	Precipitation type is very sensitive to surface air temperature; therefore, the accuracy of the vehicle-based outside air temperature data needs to be high. Data entry errors could impact the resulting precipitation type product.

7.1.4 Identification of Foggy Regions

Fog has been cited as a primary factor in multiple deadly and spectacular crashes (*20*). It often forms quickly and unexpectedly and often is limited in geographic extent. Fog is difficult to detect and predict because very slight changes in humidity and air temperature (fractions of a degree or percent, respectively) can trigger fog formation. Satellite detection of fog is difficult because cloud layers above the surface can mask lower layers. Infrared satellite processing techniques can be used to identify fog by comparing cloud (fog) top temperatures with ambient air temperature profiles. If the cloud top temperature is at or near the surface air temperature, then the cloud is diagnosed as fog. This approach is satisfactory for many applications, but not necessarily for surface transportation where fog has to be at eye level and very dense before drivers will take notice. Drivers typically do not modify their driving behavior until the visibility is less than a few hundred feet.

The meteorological community has not been able to demonstrate a lot of skill in diagnosing or predicting fog density or visibility. Visibility depends on several factors including cloud droplet size and concentration, water vapor saturation level, aerosol characteristics, and viewing angle relative to the primary light source (e.g., sun). Fog mitigation strategies for surface transportation usually involve the implementation of visibility sensors in areas prone to fog. This works well if the foggy regions are somewhat predictable, such as over waterways, valleys, or near industrial complexes that emit water vapor.

Fog and visibility detection/diagnosis and prediction could be improved with more dense and frequent surface observations of visibility, humidity, and air temperature. Because the formation of fog is highly sensitive to several variables, high quality observations are required.

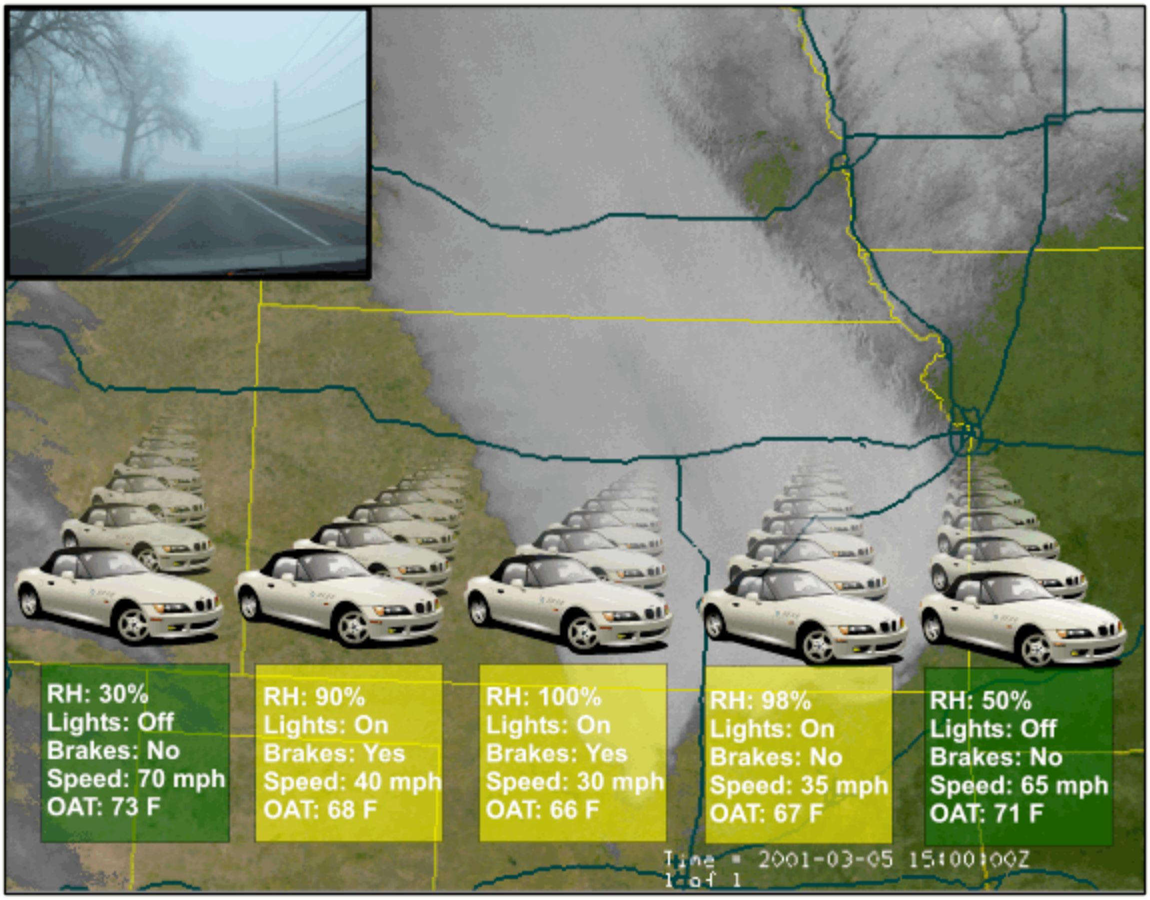

FIGURE 7.4. Conceptual illustration of vehicle data along a roadway in Kansas whereby the vehicles are moving through a foggy region. In this example, vehicle data contributing to a fog product include speed, relative humidity, headlamp setting, outside air temperature (OAT), and brake usage.

> **VII Contribution:** Vehicle data will provide an opportunity to improve fog diagnosis and prediction, but there are many challenges. Visibility measurements would provide the most direct indication of fog, but visibility is not a current or planned vehicle data element. Relative humidity measurements would also be used to diagnose fog, but are not available on standard vehicles. If a humidity data field (e.g., relative humidity, absolute humidity, water vapor mixing ratio, or dew point temperature) were available from other observational sources, then outside air temperature data from vehicles may provide insight to where fog is likely. The implementation of humidity sensors on fleet vehicles

would contribute to the solution if the fleet vehicles were well distributed.

The potential for fog formation could be computed by comparing the saturation mixing ratio of the air, which is the total amount of water vapor air can hold at a given temperature and pressure, to the actual mixing ratio, which is the actual amount of water vapor air can hold at a given temperature and pressure. When the actual water vapor mixing ratio is equal to the saturation mixing ratio, haze and fog are likely. Vehicle outside air temperature and pressure could be used in this calculation.

Driver behavior information could also be used in combination with atmospheric data to diagnose foggy regions. Fog may be present if vehicles along a specific route that had a high potential for fog (based on the previously described atmospheric calculations) slowed down, turned on their lights, and used the brakes. This concept is illustrated in Figure 7.4 where a roadway in Kansas is shown running through an area of low clouds and high humidity. The atmospheric diagnostic component of the product would indicate a high likelihood of fog and/or lower visibilities. In this example, vehicle data include outside relative humidity and air temperature, brake usage, speed and headlamps. If vehicles entered the region of high fog likelihood, and a significant percentage of vehicles reported; a) a drop in outside air temperature and vehicle speed, b) an increase in relative humidity (if available), and c) brake and headlamp usage, then the algorithm could take this into account and could either diagnose fog (deterministically) or raise the probability of fog if a probabilistic product was preferred.

Challenges: Without high quality humidity or visibility measurements, it is not likely that vehicle data will significantly contribute to this product, but it would contribute nevertheless. This product is challenging because many subtle atmospheric changes can result in the formation or dissipation of fog. The driver behavior data would contribute, but several factors could cause drivers to slow down, turn on their headlamps, and use their brakes.

A simpler concept to consider for fog identification that could utilize VII technologies is for patrol vehicles (DOT maintenance vehicles or perhaps law enforcement) to report fog locations. These reports could be entered manually into an on-board system and communicated to other transportation facilities such as traffic management centers and to traveler information systems.

Vehicle Data Applied to Diagnosing Foggy Regions		
Relevant Data Elements	**Processing Summary**	**Primary Challenges**
Time GPS Location Outside Air Temperature Relative Humidity Brake Events Headlamp Setting Fog Lamp Setting Atmospheric Pressure Manual observations from transportation operations personnel	Standard atmospheric data would be used to analyze fog potential for specific regions. Vehicle data would be used as supplemental data to confirm, raise, or lower the likelihood of fog or low visibility in specific regions.	Fog is very sensitive to surface air temperature, pressure, and relative humidity; therefore, the accuracy of the vehicle-based atmospheric data needs to be high. Knowledge of headlamp and fog lamp setting could provide some increased confidence that fog is present, but these data by themselves are not indicative of fog as drivers turn them on for many reasons. Driver behavior would contribute to the product, but great care would have to be taken as similar driver behavior would be caused by many factors in addition to fog or low visibility.

7.1.5 Improved Characterization of Surface Conditions for Weather Models

One of the biggest limitations of weather prediction is obtaining information on the current state of the atmosphere. The lack of a dense observation network, particularly west of the Mississippi River as illustrated in Figure 7.5 means that critical details about atmospheric properties (e.g., fronts, moisture, temperature gradients, wind, etc.) are missing when the current state of the atmosphere is analyzed to create the initial state for weather models. If the analyzed initial state is not a true representation of the atmosphere, then forecast accuracy will suffer.

In the last ten years, the weather research community has focused significant resources on a process called data assimilation. Data assimilation is a process whereby disparate observations are ingested, quality controlled, translated to atmospheric state variables, and objectively analyzed to produce a physically balanced state of the atmosphere on global, regional, and local scales. The data assimilation process is a critical component of the weather forecast process as it provides the ability for weather prediction models to utilize new data sets including Doppler weather radar, satellite data fields, lidar, measurements obtained from regional aircraft, non-traditional surface observations such as soil and vegetation characteristics, and others.

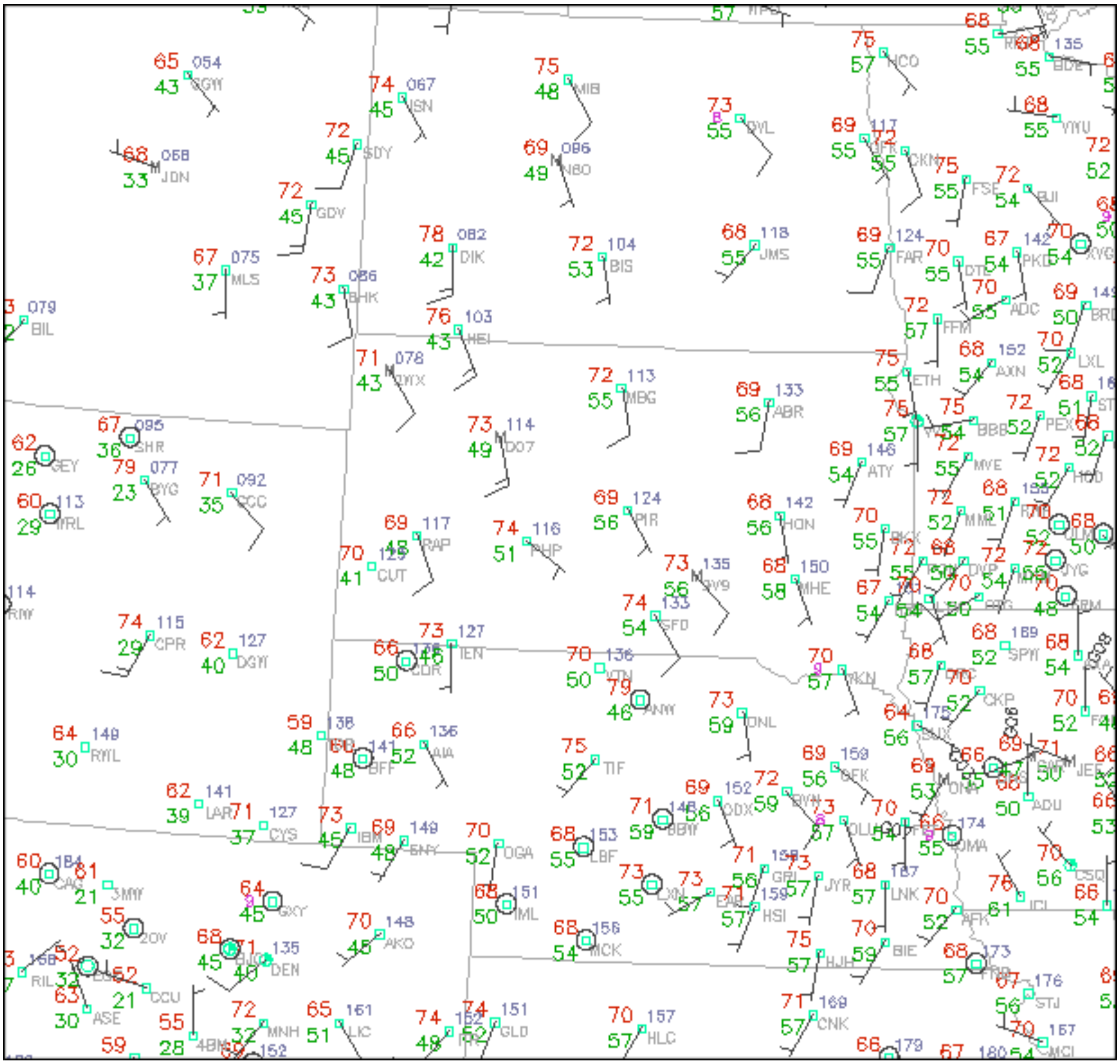

FIGURE 7.5. Graphical illustration of the NWS surface observation network in the Northern Plains States of North and South Dakota, Minnesota, Nebraska, and western Iowa. The density of surface observations decreases dramatically west of the Mississippi River.

When a sophisticated data assimilation process is utilized, the state of the atmosphere is better defined resulting in an improved forecast. As weather forecast models increase in resolution, the need for observations at high resolution increases. Ten years ago, operational weather models had a resolution of no more than 40 km, but now, advanced computing capabilities allow operational weather models to run over local regions at 1 km resolution. Future surface transportation applications will require high-resolution analyses and forecasts – down to city block scales. To support this requirement, high resolution models will be needed, which in turn will require very high resolution initialization data. Vehicle data will contribute to the observational database at or near the ground. A better representation of the atmosphere at the ground is important as road conditions are determined by the atmosphere-pavement interface.

> **VII Contribution:** Vehicle data can be used to fill the gaps in the surface observation network. The most important atmospheric variables include air temperature, pressure, wind, and water vapor. It would be optimal if all these variables were available from vehicles, but they are not. Presently, vehicle data include air temperature and pressure. Relative humidity would be the next most important variable, but accurate water vapor/humidity sensors are expensive and require frequent calibration. The overall impact that vehicle data will have on weather prediction models will depend on several factors including the configuration of the model, mainly domain size and grid spacing, number and distribution of standard surface observations in the model domain, and ability of the modeling system's data assimilation system to process the data. If a weather model was configured to have a 5 km grid spacing and the standard observational sites were, for example, 20 km apart, vehicle data (e.g., outside air temperature and pressure) in between the standard sites would contribute as they would help define the state of the atmosphere on a scale closer to that of the model.
>
> An example of this can be found in Figures 7.6 and 7.7. The figures show the passage of a simulated cold front through the Detroit Metropolitan area. The contour pattern found in Figure 7.6 was constructed using a tension spline interpolation technique based on simulated temperature data from the ASOS stations in the region, which are also displayed in the image. The contours are very smooth and provide limited information about the temperature field in the region, particularly on city-block scales. The contour pattern found in Figure 7.7 was produced using the same interpolation technique; however, simulated data from 165 vehicles on interstates within the domain of interest are incorporated in the analysis. The change in the temperature field is substantial, as more detail is provided by including vehicle data. Within the field of view of Figures 7.6 and 7.7, there are over 1.7 million households. Assuming that each one of these households had one vehicle

transmitting data to the VII network during the day, the magnitude of the impact of these data on analyses such as the temperature field would be immense.

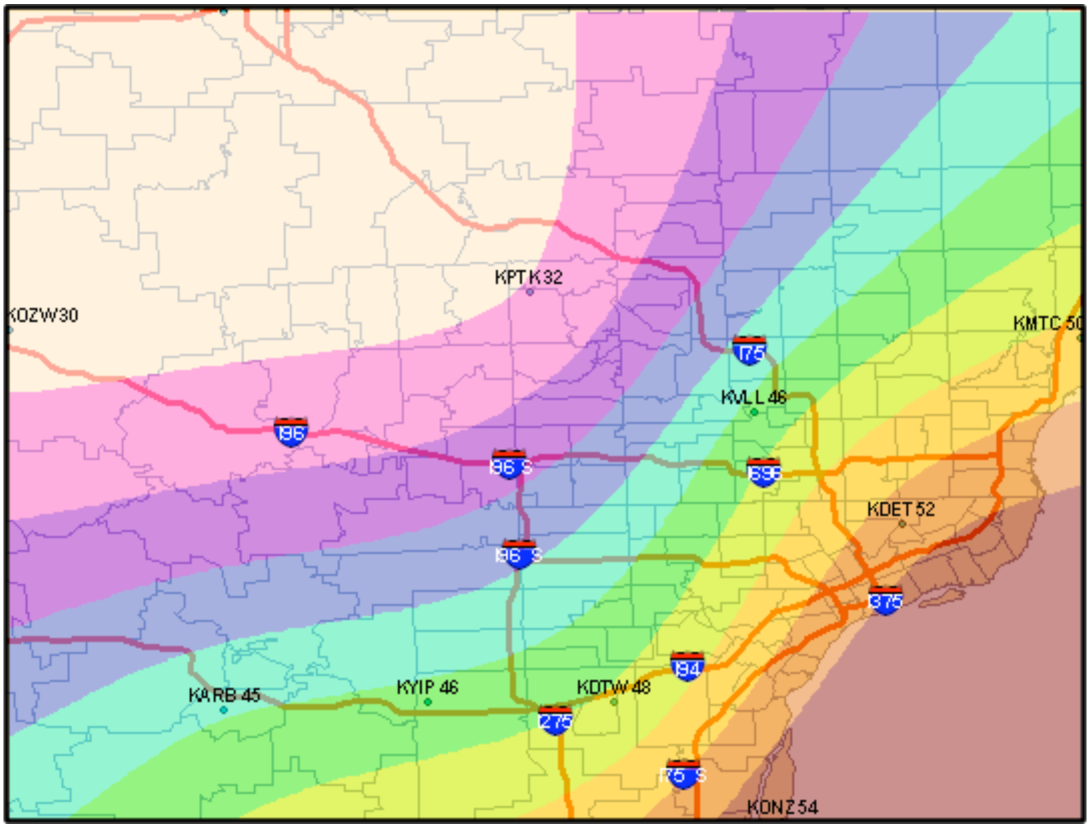

FIGURE 7.6. Contours of temperature in the Detroit area during the passage of a simulated cold front. Warmer temperatures are in the southeast, and colder temperatures are in the northwest. Contours are based on simulated data from area ASOS stations.

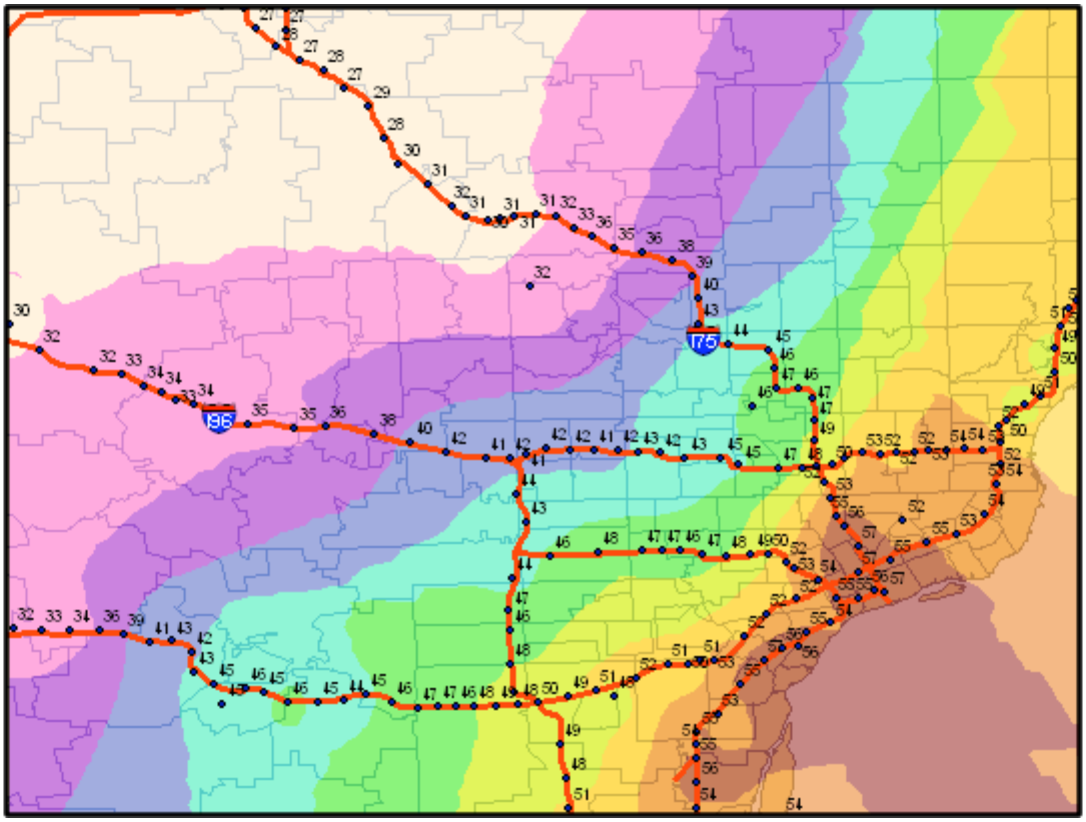

FIGURE 7.7. As in Figure 7.6, except simulated data from 165 vehicles located along the interstate highways are included in the analysis.

Challenges: Data quality and data representativeness remain challenges. Data quality is partially addressed by weather model data assimilation systems as these systems utilize variational approaches and error statistics to filter data. In addition, the laws of physics are applied to ensure that the initial state of the atmosphere is physically realistic and balanced.

Determining the representativeness of the vehicle data will pose a challenge. If a weather model is configured to run with a small grid spacing (fine mesh), then it is appropriate that the initialization data match the fine grid spacing and resolve micro-climates. If a model is run at a lower resolution, then the initialization data does not have to represent the finest scales.

The data assimilation methods and techniques used to calculate and deliver vehicle data to a weather modeling system will depend on the desired model output resolution, but will likely involve statistical approaches to filter the data. For example, if the weather model was configured to have a 5 km grid spacing, then there is no need to provide hundreds or thousands of individual vehicle data samples within the model's grid cell. There is no need to over-sample the data, as this would waste precious computer processing resources. A single representative data sample would be sufficient; therefore, it is likely that the vehicle data would be pre-processed to derive a statistically representative sample at a temporal and spatial resolution appropriate for the model configuration.

High-resolution surface observations of atmospherics state variables contribute significantly to the diagnosis and prediction of weather and road condition products. High-resolution measurements of air temperature, water vapor (humidity), pressure, wind speed, and wind direction are highly desired, but only air temperature and pressure are currently available from vehicles.

As mentioned in section 5, it is not practical, at least in the short term, for vehicle manufacturers to instrument vehicles with sensors that can measure all the desired atmospheric variables. Again, another possible approach would be to instrument a subset of vehicles with additional sensors. Vehicle fleets that have broad coverage on a daily basis would be good candidates for these sensors.

Improved Initialization of Surface Conditions for Weather Models

Relevant Data Elements	Processing Summary	Primary Challenges
Time GPS Location Outside Air Temperature Relative Humidity Atmospheric Pressure	Statistical methods would be applied to individual vehicle data samples to determine a representative data sample (appropriate temporal and spatial resolution) for a given weather model configuration (grid spacing, model cycle update period, and forecast resolution)	Data quality of individual data samples will be the primary challenge. Statistical processing to calculate a representative sample will mitigate some of the effects of poor data quality. Additional processing through the model's data assimilation system will mitigate or reduce the impact of poor data.

7.1.6 Improved Weather Analysis and Prediction in Complex Terrain

The lack of weather observations in complex terrain complicates an already difficult weather analysis and forecast problem. Operational weather forecasting models, which are typically configured with a grid spacing of 20 to 40 km, are unable to resolve the complexities of the precipitous terrain where steep slopes prevail. Traditional weather models are unable to resolve the detailed vertical motions that determine where clouds and precipitation will form in and around hills and mountains. Wind is also channeled around terrain and these diverging and converging motions impact the weather.

As the resolution of weather models increase, the ability to resolve the wind flow increases. There is also a corresponding need to increase the density of observations to support the model resolution.

The lack of observations also impacts the ability of transportation officials to respond to rapidly changing conditions as they do not have the ability to monitor the situation. Winter maintenance professionals are often faced with situations where they do not know the freezing level (rain/snow level) along mountainous routes. The lack of information can lead to wasted or miscalculated snow and ice control actions.

Vertical profiles of weather and road conditions could also support weather analysis and forecasting activities. An atmospheric sounding diagram (SKEWT/LOG-P) taken by the NWS in Denver, Colorado is shown in Figure 7.8. For discussion purposes, only the lowest portion of the sounding is shown. The sounding shows air temperature and dewpoint temperature measurements at various atmospheric pressure levels[8]. Air temperature and water vapor profiles from the surface (approximately 860 hPa or 5280 ft in Denver) to approximately 20,000 ft (450 hPa) are shown.

The data show a strong nocturnal inversion in the fewest hundred feet and very dry and warm air above. Forecasters use sounding data to characterize atmospheric stability, cloud base and tops, freezing level(s), troposphere depth, jet stream strength, winds aloft, vertical shear of the horizontal winds, and many other factors. Soundings are only taken twice a day at 00 UTC and 12 UTC, so forecasters have the challenge of assessing how the sounding will change over time.

Additional data in the lowest levels of the atmosphere would help forecasters and forecast systems as it would provide information on how the atmospheric boundary layer is evolving over time. For example, knowledge of when an inversion will disappear provides key information on the daily temperature and humidity trends, cloud and/or thunderstorm formation, fog dissipation, etc. Wind and temperature data from commercial aircraft have been used

[8] Atmospheric pressure is measured in hecta Pascals or millibars. On average, sea level pressure is 1013.25 hPa. In Denver, the average surface pressure 860 hPa.

successfully by weather forecasters and forecasting systems over the last decade to supplement traditional soundings.

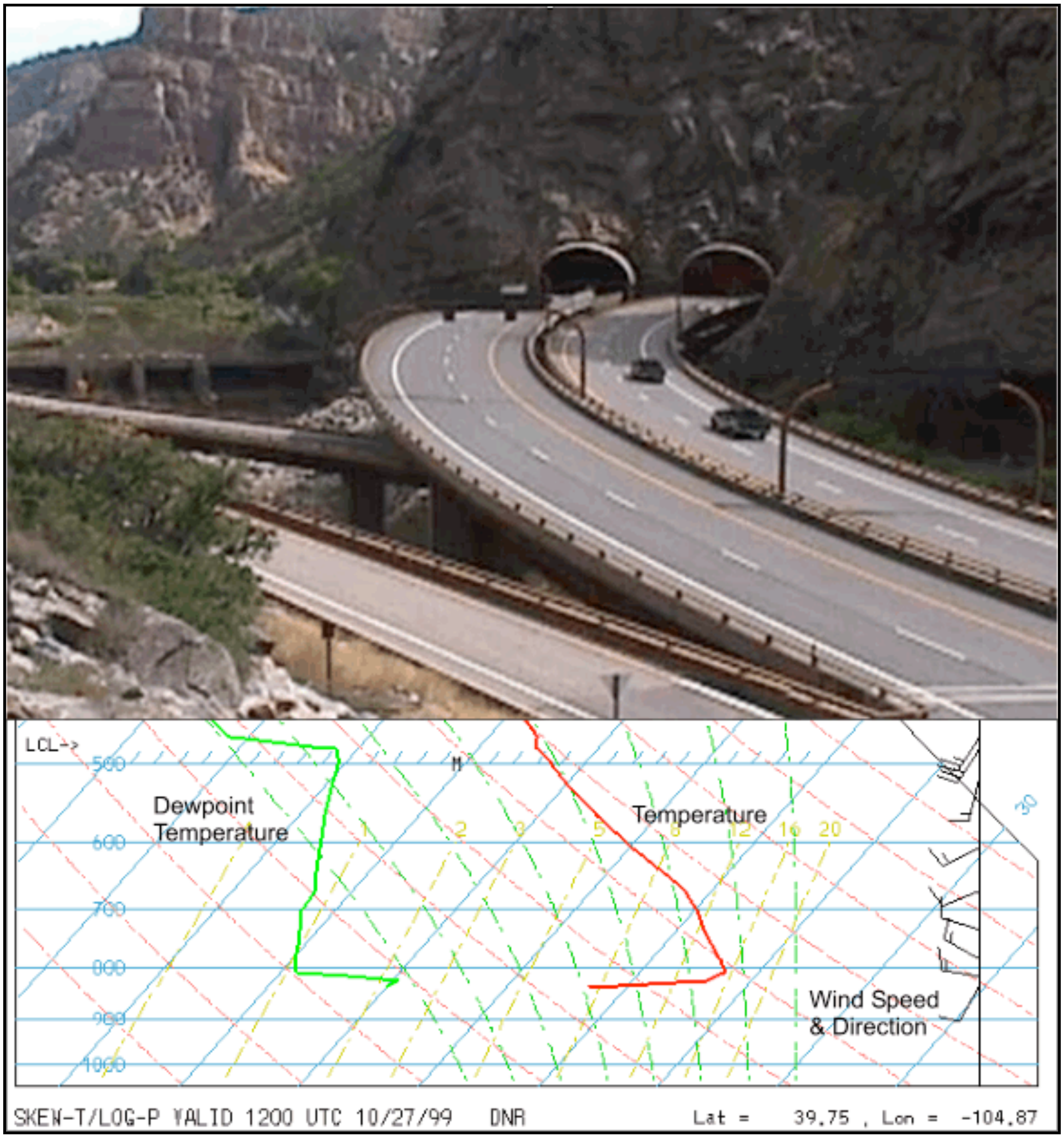

FIGURE 7.8. Photo of winding road through complex terrain (top) and bottom half of a SKEWT/LOG-P atmospheric sounding diagram (bottom) from Denver, Colorado on October 27, 1999. The (partial) sounding diagram shows air temperature and dewpoint temperature measurements plotted at different altitudes (pressure levels) from a NWS balloon sounding. The data indicate that a very strong inversion was present in the lowest few hundred feet of the atmosphere near Denver. Wind barbs (right side) indicate wind speed and direction and pressure (left axis) is on hPa. For reference, 700 hPa is approximately 10,000 ft above sea level. Data collected by vehicles in

mountainous areas could provide additional information (temperature, pressure, etc.) about the vertical structure of the atmosphere beyond what is currently supplied by traditional atmospheric soundings.

VII Contribution: Although roads typically do not traverse the most complex terrain, there are substantial roadway networks in mountainous states. Weather and road condition data collected along these roads would provide valuable information to forecasters, transportation officials, and travelers.

The implementation of RWIS along roadways has already had a positive impact on mobility because winter maintenance personnel are able to monitor the weather and road conditions and take a proactive approach to winter maintenance. RWIS data are also used as input to traveler information systems providing the public with weather and road condition information. The primary limitation with RWIS is that they only represent the conditions at the fixed site, and in most cases, the stations are tens to hundreds of miles apart. In complex terrain, weather and road conditions can change dramatically over just a few miles.

Vehicle data will provide not only detailed information on the weather and road conditions along mountainous roads, but also information at various elevations along the route. The vertical information would dramatically improve the ability of winter maintenance officials to determine the atmospheric and pavement freezing levels and develop more precise winter maintenance strategies.

Vehicle data would also help forecasters and forecast systems fine tune their products by providing critical information on the horizontal and vertical structure of the lower atmosphere and how it is evolving with time. Vehicle data relevant for supporting the weather analysis and forecast process include outside air temperature, pressure, wiper settings (for precipitation assessment), and relative humidity.

Challenges: Data quality and data representativeness remain challenges. Data quality could be partially addressed through statistical processing and by weather model data assimilation systems. The accuracy of GPS data is also a concern as satellite signals are often lost in the mountains and elevation data are typically only accurate to within a couple hundred feet. Vehicle elevation data could be corrected using knowledge of the location information if the roadway elevations were sufficiently known. Although vehicle data collected at various elevations could be considered similar to a sounding, the profiles along roadway will not represent the free atmosphere[9]. Care will have to be taken to ensure that the data are utilized properly.

Improved Weather Analysis and Prediction in Complex Terrain		
Relevant Data Elements	**Processing Summary**	**Primary Challenges**
Time GPS Location Outside Air Temperature Relative Humidity Atmospheric Pressure Windshield Wipers (front) On/Off Manual observations from transportation operations personnel	Vehicle data from multiple altitudes would be used to construct a vertical profile along routes in complex terrain. The vehicle data would supplement standard weather observations from fixed sites (e.g., NWS and RWIS sites). The data would also be used to support tactical operations (e.g., identifying freezing levels, precipitation occurrence and type) and as input (mini-soundings) to weather models.	Data quality of individual data samples will be the primary challenge. Accuracy of GPS position data, particularly elevation data, may be degraded due to terrain obscurations. Statistical processing may be required to calculate representative samples at various elevations and locations along routes.

7.1.7 Improved Air Quality Monitoring and Prediction

Due to Environmental Protection Agency (EPA) regulations, major urban areas are required by law to monitor and predict air quality and institute restrictions and public alerts when air quality thresholds are exceeded or predicted to be exceeded. The two major factors that affect air quality are the weather and pollution sources. In many urban corridors, vehicle emissions are the dominant pollution source. The number, type, and distribution of vehicles throughout the urban corridor determine the amount of pollution that is generated.

Air quality models calculate the change in pollutant concentrations over time and space. They require meteorological inputs that, in part, determine the formation, transport, and destruction of pollutants. The requisite meteorological inputs vary by air quality model, but usually include data on wind speed and direction, vertical mixing, temperature and atmospheric moisture.

According to the EPA, "air quality modeling strives to replicate the actual physical and chemical processes that occur in an inventory domain [urban

[9] The free atmosphere refers to the portions of the atmosphere that are not directly influenced by the Earth's surface.

corridor], it is important that the physical location of emissions be determined as accurately as possible. In an ideal situation, the physical location of all emissions would be known exactly. In reality, however, the spatial allocation of emissions in a modeling inventory only approximates the actual location of emissions."

Decision support systems have been developed to help local authorities manage air quality programs. The decision support systems utilize current and predicted weather information and empirical information about pollution sources including traffic information, vehicle demographics (number, make, model), and emission characteristics for each vehicle type. In most instances, information about the emission sources is based on statistical averages (e.g., normal traffic and congestion patterns) and not real-time conditions.

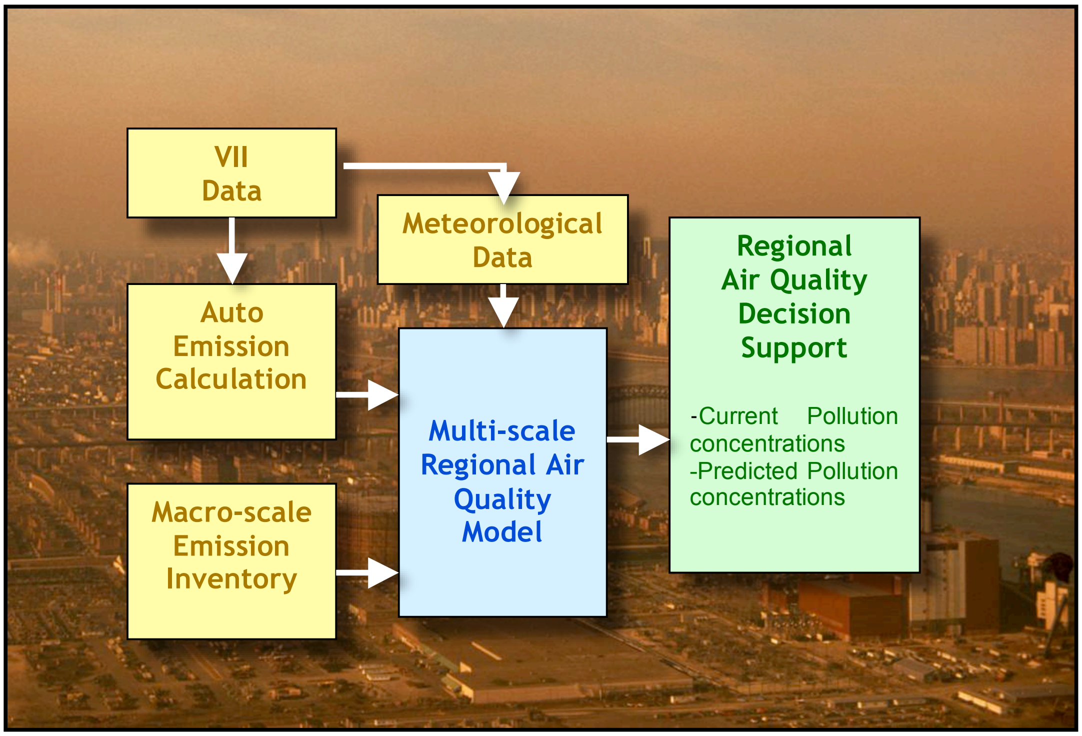

FIGURE 7.9. Generalized data flow for air quality models. Vehicles would provide real-time data that would contribute to the calculation of emission rates.

VII Contribution: Information on vehicle type and location would be used in air quality analysis and prediction models to improve real-time estimates of the emission sources. A dynamic (constantly updating) database of vehicle data would provide a rich source of new data for these models. Vehicle generated air temperature data in the urban corridor could help identify micro-climates and characterize boundary layer inversions for example, which are both very important factors in air quality monitoring and prediction. Improved estimates of precipitation would improve calculations of pollution sinks.

Challenges: Vehicle data quality is the primary concern, as air quality models, like most models, are sensitive to input data. Statistical processing can be used to remove outliers and data assimilation systems would provide an opportunity to filter data of poor quality. Data on the chemical makeup of the exhaust would contribute directly to the solution.

Vehicle Data Applied to Improving Air Quality Monitoring

Relevant Data Elements	Processing Summary	Primary Challenges
Time GPS Location Air Temperature Windshield Wipers (front) On/Off Precipitation Sensor Emissions data Vehicle Type	Air temperature and data elements that provide indications of vehicle type would be the most relevant data elements for this application. Information about precipitation could also be used as input for pollution sink calculations.	Data quality and representativeness. Identifying occasions when wipers are used or precipitation sensors are responding to splash-back when no precipitation is occurring. If a rain sensor is used as the primary data source, one has to be aware that it will not likely record frozen precipitation.

7.1.8 Improved Diagnosis of Boundary Layer Water Vapor

As mentioned throughout this report, improving our knowledge on the distribution of atmospheric water vapor is critical for improving weather and road condition analyses and forecasts. Today, vehicles do not directly measure water vapor, but through VII, they may be able to contribute in the future to a new radar-based technology that shows significant promise for diagnosing water vapor in the boundary layer.

The electromagnetic frequencies utilized by weather radars are sensitive to atmospheric temperature, pressure, and water vapor. If temperature, pressure, and electromagnetic phase are known, then atmospheric refractivity can be calculated. A new research program titled Refractivity Experiment for H_2O Research and Collaborative Operational Technology Transfer (REFRACTT) was conducted in 2006 to determine the feasibility of diagnosing water vapor from refractivity measurements. The Denver WSR-88D and nearby research radars were used in the experiment. Known ground targets were used to determine phase shift and this information along with local surface measurements of temperature and pressure were sufficient to calculate refractivity. Water vapor remained the only unknown; therefore, water vapor variability within the radar sensing area could be diagnosed.

Figure 7.10 shows the refractivity field from the Front Range WSR-88D near Denver for the 0.5 degree elevation scan from 10 September 2006. Refractivity is shown in non-dimensional "*N*" units. A 1 g/kg change in atmospheric moisture is equivalent to 4 *N* units. This example illustrates the variability in moisture in and around the Denver area. The moisture discontinuities can be used to improve the prediction of precipitation.

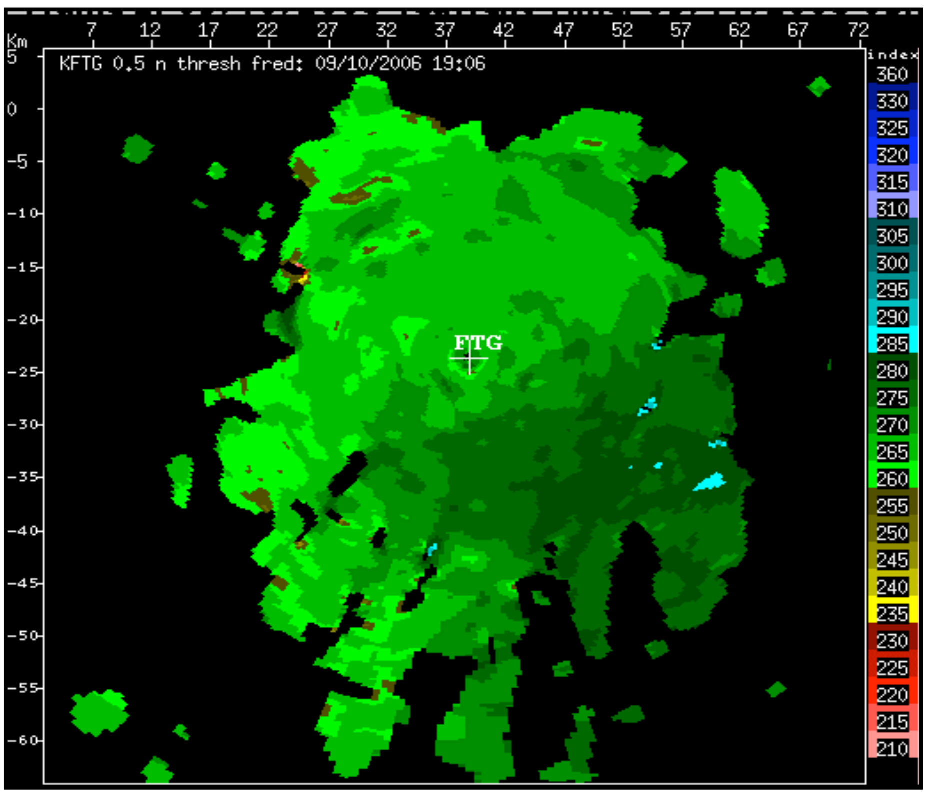

FIGURE 7.10. Refractivity field from the Front Range WSR-88D near Denver for the 0.5 degree elevation scan from 10 September 2006. Refractivity is provided in non-dimensional "*N*" units. A 1 g/kg change in atmospheric moisture is equivalent to 4 *N* units. The figure illustrates a moisture gradient from south to north.

This research project was able to document water vapor gradients caused by thunderstorm gust fronts, cold fronts, dry lines, and drying from downslope flows. The data were also useful in nowcasting thunderstorm initiation.

Scientists indicated that additional skill in diagnosing water vapor could be obtained by utilizing additional surface pressure and temperature data. The distribution of ASOS stations is marginally sufficient to support this technique. Knowledge of the detailed pressure and temperature fields within the radar measurement region are critical for this application.

> **VII Contribution:** Atmospheric pressure and temperature data are available from vehicles. The high concentration of data provided by the VII network would directly contribute to the calculation of water vapor using the methods tested in the REFRACTT project. If additional testing proves successful, it is likely that this technique will be implemented in the national WSR-88D network thereby creating the need for additional temperature and pressure data.

Improved Diagnosis of Boundary Layer Water Vapor		
Relevant Data Elements	**Processing Summary**	**Primary Challenges**
Time GPS Location Outside Air Temperature Atmospheric Pressure	Air temperature and atmospheric pressure data would be utilized by weather radar refractivity algorithms to diagnose water vapor fields.	Ensuring accurate outside air temperature and atmospheric pressure data.

7.2 Pavement Condition Product Improvements Enabled by VII

Examples of pavement condition products that will be improved with vehicle data are presented in this section. The examples provide only a sampling of what will be possible with these new datasets. The product examples include both improvements in the diagnoses of current pavement conditions and in road condition prediction. Pavement conditions not directly associated with weather, such as potholes, are not included in this discussion.

Road condition improvements that will be enabled with vehicle data include, but are not limited to:

- Improved identification of slippery pavement
- Improved knowledge of pavement temperatures

- Improved knowledge of pavement condition (dry, wet, snow covered, etc.)

7.2.1 Improved Identification of Slippery Pavement

Research has been conducted and is ongoing to evaluate the applicability of friction data from probe and winter maintenance vehicles to assess roadway condition (*21*). The primary purposes of this research are to evaluate the ability of vehicle probe data to be used to derive friction as an objective measure of pavement level of service and as a winter maintenance performance metric. The results of using friction information for this purpose have been mixed for several reasons. First, several approximations must be made and theoretical models used to estimate friction from vehicle data, mainly ABS. Second, there have been difficulties manufacturing friction measuring devices that operate properly under the extreme conditions associated with winter maintenance operations. In addition, pavement friction varies greatly over small distances and with time makes it difficult to determine what constitutes a representative sample. Pavement friction also varies with pavement and tire type. Nevertheless, friction information can provide a measure of road condition relative to the normal state (e.g., dry road).

Anti-lock Braking Systems (ABS) are designed to keep wheels from slipping by applying just enough braking action to maximize the friction between the pavement and each tire. Although ABS does not directly measure friction, it may be possible to derive information on the state of the roadway from ABS event data.

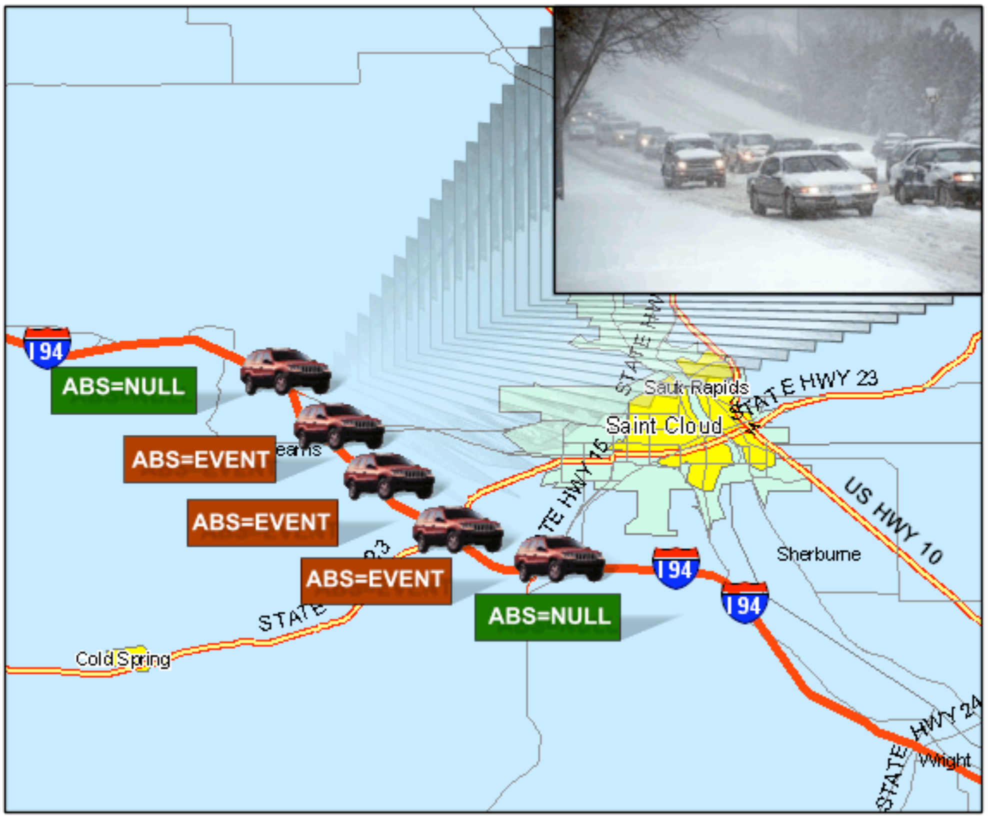

FIGURE 7.11. Conceptual illustration of a VII-enabled road condition product that provides users with information on Anti-lock Brake System (ABS) status. Positive reports of ABS events from multiple vehicles could provide winter maintenance personnel with information that suggests that pavement friction is low in specific regions. Travelers in the vicinity of vehicles reporting ABS events could also receive notifications of the activity as a "heads-up" advisory.

VII Contribution: Vehicle manufacturers indicate that ABS event data (on/off) are available and could be disseminated for use in external applications. Although friction data are not available, event data would be used to diagnose slippery conditions should a certain population of vehicles report ABS events.

Figure 7.11 is a conceptual illustration of a VII-enabled road condition product that provides users with information on ABS status. Null reports are not generated by vehicles, but are shown in the figure to illustrate the end points of the region of interest. Positive reports of ABS events from multiple vehicles could provide winter maintenance personnel with information that suggests that pavement friction is low in specific regions. Positive ABS report information would also be utilized by winter maintenance decision support systems such as the Maintenance Decision Support System (MDSS) to identify road segments that may need additional treatment. The notification information would also be utilized by traffic managers as it would signal locations were vehicles are slowing or attempting to slow, which also may result in congestion. Incident management personnel may also be interested as locations of multiple ABS events may indicate a trouble spot that deserves additional attention.

Travelers in the vicinity of vehicles reporting ABS events would receive notifications of the activity as a "heads-up" advisory.

Challenges: Slippery conditions may exist in locations that generate no ABS events and ABS events may exist without slippery conditions. Drivers that gradually slow on icy roads may never generate an ABS event even though friction may be very low. On the other hand, ABS events could be triggered by rapid braking on dry pavement or light braking on unpaved roads. Determination of pavement slipperiness will require the integration of multiple datasets (precipitation type and rate, pavement temperature, manual reports, video imagery, etc.) where ABS event data is only one component. Systems such as the winter MDSS, which contains many of the relevant datasets, may provide a suitable host for this product concept.

Improved Identification of Slippery Pavement		
Relevant Data Elements	**Processing Summary**	**Primary Challenges**
Time GPS Location ABS Event (on/off) Stability Control Outside Air Temperature Pavement Temperature	ABS event data would be statistically analyzed over specific routes or within a certain distance of the ABS report to determine data confidence. The processed ABS event data could be provided to transportation users as an individual product or as a component of a broader product that combines weather and other road condition information.	Slippery conditions may exist in locations that generate no ABS events and ABS events may exist without slippery conditions.

7.2.2 Improved Knowledge of Pavement Temperature

Pavement temperature is the most critical factor in winter snow and ice control operations. It is also important for pavement striping and construction. Pavement temperature is currently measured by temperature sensors embedded in the pavement and also by infrared devices mounted on maintenance vehicles. Pavement temperature can vary dramatically over short distances due to variations in road characteristics (e.g., asphalt vs. concrete), road orientation, shadowing characteristics, and the amount of contamination on the road (snow, ice, leaves, water, etc.).

Current fixed measurement systems can only provide an indication of the pavement temperature at the measurement site. Transportation operations personnel, particularly winter maintenance practitioners, need to know the pavement temperatures along the entire roadway system so they can assess the likelihood that snow or ice will accumulate. Pavement heat-balance models, such as those utilized by the MDSS, require accurate weather, pavement, and subsurface temperature information. Vehicle generated pavement surface temperature data would benefit the MDSS, as the data could be used to initialize pavement temperature models. Travelers could benefit from pavement temperature information so they can assess the likelihood that precipitation will freeze or snow will accumulate at their location and on nearby road segments.

Figure 7.12 is a conceptual illustration of a graphical pavement temperature product over central Iowa that includes both fixed sites (Iowa RWIS) and vehicle data. In this example, there is a pavement temperature gradient from above to below freezing along I-35. The location of the freezing pavement cannot be determined from the RWIS alone as the sites are more than 50 miles apart. Vehicle data supplement the RWIS data and provide a more precise indication of the location of below freezing pavement temperatures.

FIGURE 7.12. Conceptual illustration of a graphical pavement temperature product over central Iowa that combines data from both fixed sites and vehicles. Iowa DOT RWIS sites are shown as yellow diamonds with RWIS pavement temperature values shown in selected white boxes. Vehicle measured pavement temperatures are shown along I-35 in blue boxes. The vehicle data help define the location of freezing pavement temperatures between the fixed RWIS sites.

Thermal mapping of roadways is sometimes performed to assess the relative differences in pavement temperature from actual measuring sites. Infrared temperature measurements are made along the entire roadway between observation points and are used to diagnose the temperature along the roadway where no actual temperature measurements exist. The primary benefit of thermal mapping is that it provides an estimate of the pavement temperature along the entire roadway network. The limitation of thermal mapping is that it does not provide actual measurements of pavement temperature. In addition, the thermal mapping process needs to be redone when the characteristics of the pavement change (e.g. paving).

Pavement temperature is not one of the data elements currently envisioned for the mass market, but if it were available, it would provide very useful information to both travelers and transportation operations personnel. The benefits of knowing pavement temperature have proven themselves to the winter maintenance community, and in response, an increasing number of embedded pavement temperature sensors are being installed in the roadways and an increasingly larger fraction of winter maintenance vehicles have been equipped with infrared pavement temperature sensors.

VII Contribution: Pavement temperature information along the entire roadway network is important for the reasons mentioned above. Vehicle data would provide a more continuous data set along the highway than is available from fixed sensors. Vehicle data would not eliminate the need for embedded sensors as the fixed sensors provide data even when no vehicles are present. Pavement temperature information is required around the clock to support winter maintenance operations.

Vehicle sensed pavement temperature and sun sensor data would also be useful for pavement temperature prediction. Pavement heat balance models perform better when they have been initialized with actual pavement temperature and local air temperature data. Vehicle data would improve the performance of heat balance models for sites that are not equipped with fixed sensors. Information on the subsurface temperatures could be used in the models from nearby fixed sites if the sites are close and are likely to have similar subsurface temperature profiles. Sun sensor data (watts/m^2) could also be used to diagnose the intensity of direct solar radiation. The sun sensor data could be used in the pavement heat balance model to adjust the solar radiation values at the initial time step.

Drivers would also benefit from knowledge of pavement temperature as it would provide an indication that the road is near freezing. Drivers could use this information to assess the likelihood that precipitation may freeze or that black ice may exist.

Challenges: Infrared temperature sensors, which are the most commonly used technology for mobile pavement temperature sensing, are prone to errors if they are not routinely calibrated. Because they are not in contact with the surface, heat from the surrounding environment can influence the temperature measurement. This makes the placement of the device challenging, as it needs to be as close to the pavement as possible, but not in a location that could be contaminated by road splash or engine and exhaust system heat.

Because infrared devices are remote sensors, roadway contaminants such as snow, ice, and leaves, will influence the temperature measurement. The sensor measures the temperature of whatever is in its sample volume; therefore, if the material on the pavement is not the same temperature as the pavement, the sensor will report the material temperature. Temperature differences can also be expected between embedded sensors ("pucks") and infrared sensors because embedded sensors measure the pavement temperature slightly below the pavement surface, while infrared sensors measure the pavement surface temperature.

Improved Knowledge of Pavement Temperature

Relevant Data Elements	Processing Summary	Primary Challenges
Time GPS Location Pavement Temperature Outside Air Temperature Sun Sensor	Vehicle pavement temperature data would be processed to generate a statistical sample for a given stretch of roadway. The calculated pavement temperature would be quality checked by comparing it to nearby fixed sensors, where available. Vehicle air temperature would be handled in a similar manner. The vehicle based pavement temperature data would be provided to end users for user-defined locations. Sun sensor data (watts/m^2) would also be used to diagnose the intensity of direct solar radiation. The sun sensor data could be used in the pavement heat balance model to adjust the solar radiation values at the initial time step.	Infrared temperature sensors are prone to errors if not routinely calibrated. They also have to be sited carefully as they will sense heat from the nearby the environment. Road splash can also result in errors. The temperature of the sensor housing must also acclimate to the outside environment, so the data should not be used until equilibrium exists.

7.3 In-Vehicle Information System Products Enabled by VII

VII technology will not only enable vehicles to communicate probe data to external systems, but it will enable safety and mobility related products to be delivered to vehicles. When drivers enter their vehicles, they are usually cut-off from normal information sources such as television and the Internet, and until cell phone technology became dominant, phone service was unavailable. Wireless communication technologies are becoming more reliable, more widespread, and less expensive, which is providing an enormous opportunity for the automotive, consumer electronics, and telecommunication industries. The widespread adoption by the public of wireless vehicle technology is just around the corner.

An energetic debate has arisen about the product content that will be provided in vehicles. Safety and mobility-related products such as curve speed warnings, work zone and congestion advisories, and lane departure warnings will likely be provided as well as several other products, which are now on the drawing board. Weather and road condition information cover both safety and mobility concerns, but it is not clear at this time how the automotive industry views weather and road condition information. At present, it appears that weather and road condition information falls somewhere between critical and nice to know. Certainly, an argument can be made that providing information to the driver about imminent hazardous weather and road conditions will result in some fraction of the drivers modifying their behavior, which should result in improved safety. Avoiding areas of hazardous weather and/or road conditions can not only improve safety, but also mobility if a more efficient route was selected.

Properly engineered in-vehicle information systems that couple navigation technologies with dynamic weather and road condition information may also help consumers justify their contribution to the national VII dataset. Vehicle owners may be more willing to provide vehicle data if they know that they will be a direct beneficiary of the data. In-vehicle weather and road condition data may provide that justification.

Weather and road condition products should be provided in simple graphical and text form and critical information should include an audible advisory. Except for destination weather information, products based on forecasts should be avoided. The focus should be on tactical products – current conditions and nowcasts (0 to 1 hour). Figures 7.13 and 7.14 show examples of potential in-vehicle weather displays enabled by VII. Figure 7.13 indicates a segment of highway that has been identified as hazardous due to slippery conditions, and Figure 7.14 displays weather radar data along with the road condition alert. Note that other information such as nearby environmental sensor data, national weather service advisories, and traffic alerts could be included as well. In-vehicle weather and road condition products that are likely to be of the most interest to drivers include:

- Heavy rain
- Heavy snow
- Hail
- Dense fog
- High winds
- Tornados
- Severe thunderstorms
- Ground blizzards

- Flooding
- Blowing dust
- Smoke

The following weather warnings should also be provided to drivers for their specific location:

- Tornado warning
- Severe thunderstorm warning
- Flash flood warning
- Blizzard warning
- Hurricane warning
- Winter storm warning
- Ice storm warning
- Tropical storm warning

VII Contribution: VII provides the technology infrastructure to deliver vehicle data (probe data) to external processing systems that will utilize the VII data to improve weather and road condition products and provides the capability to return processed products to the driver. The utilization of VII data will improve the likelihood that road weather products will be more accurate because the products will utilize data measured along the same roadway segment by other vehicles. Errors associated with temporal or special interpolation should be reduced since VII will provide a much larger data sample than fixed stations, thus reducing the need to interpolate.

Challenges: Vehicle drivers are the ultimate verification system for in-vehicle information. Drivers will not likely tolerate many false alarms. Product accuracy in timing and event location will be critical. The human factors aspects of designing weather and road condition products should be taken seriously to ensure that the products add value and do not interfere with the driving environment. Drivers should be presented with road weather products that are clear, concise, and easily accessed. This will be particularly important in instances where a driver is unfamiliar with a vehicle (e.g. rental car). User configuration will also be critical. Users should be able to pre-configure the product information that is of interest to them. Only products of interest and relevant (route specific) to the driver should be provided.

FIGURE 7.13. Conceptual illustration of an in-vehicle navigation display containing VII-enabled weather alerts. In this example, an alert for slippery road conditions is displayed notifying the driver of hazardous conditions prior to the encounter. (Courtesy of Andrew Stern - Mitretek Systems)

FIGURE 7.14. Conceptual illustration of an in-vehicle navigation display containing VII-enabled weather alerts overlaid with weather radar data. In this example, the vehicle is about to enter a region of heavy precipitation (Courtesy of Andrew Stern - Mitretek Systems)

7.4 Transportation System Management Decisions Supported by VII

In addition to VII contributing to improvements in the analysis and prediction of weather and road conditions, it will contribute valuable data and information to transportation Decision Support Systems (DSS) and transportation decision makers including traffic, incident, and emergency managers, and maintenance personnel. In this section, a brief description of how VII could support DSSs and specific decision makers is provided.

7.4.1 Maintenance Decision Support System (MDSS)

The MDSS represents the first successful integration of advanced weather and road condition prediction systems, numerical model output, chemical concentration algorithms, and anti-icing and deicing rules of practice in a single decision support system; MDSS provides specific anti-icing and deicing treatment guidance (timing, location, type and amounts) for a wide range of weather and road conditions along specified winter maintenance routes. Effective snow and ice control involves making decisions on a series of complex processes that depend on road and bridge temperatures, precipitation type, liquid equivalent, chemical concentration, chemical type, wind speed, frost potential, and whether to pre-treat roads and/or pre-wet chemicals prior to storm events.

One of the requirements of the MDSS is that the actual treatment actions be available to the system so that they can be factored into future treatment recommendations. This process is cumbersome as it currently involves manual entry of treatment plans into the MDSS. VII technology, when coupled with maintenance vehicle recording devices, would allow the actual treatments to be communicated in near real-time to the MDSS without manual intervention. This will significantly reduce the workload of winter maintenance supervisors and operators. Figure 7.15 shows the FHWA prototype MDSS interface for entering actual treatments.

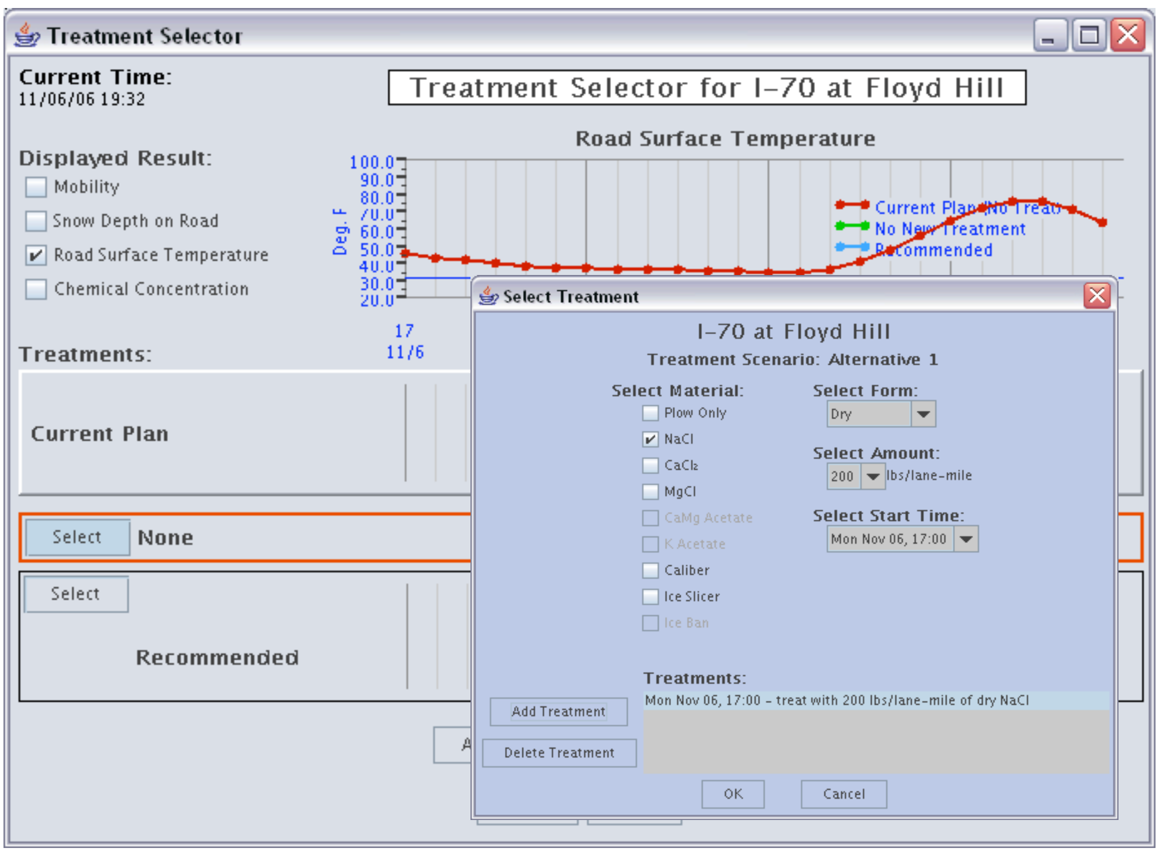

Figure 7.15. Sample image from the FHWA prototype MDSS for a plow route along Interstate 70 near Denver, CO. Winter maintenance personnel use this dialog (inset image) to enter the actual snow and ice control treatments and to explore alternative treatments. Treatment type, amount, and timing can be entered.

Vehicle data such as air and pavement temperature, ABS, vehicle stability control, and wiper settings could be also utilized by the MDSS in near real time. Air and pavement temperature data would be used to initialize the weather and road condition algorithms during each update cycle; ABS and vehicle stability control could be used within the MDSS to alert winter maintenance personnel to road segments that may need additional attention.

Vehicle probe data of air temperature coupled with wind data from RWIS or other surface observational data sources could be used to calculate local windchill temperatures, which could be use to alert maintenance staff of unsafe conditions.

7.4.2 Traffic and Incident Management

Vehicle data will provide valuable information on the state of the roadway directly to traffic managers. Traffic and congestion are sensitive to weather and road conditions. Transportation network maps that highlight wiper usage, for example, could be used by traffic and incident managers to raise their awareness that precipitation has started or that visibility is reduced due to road spray. This could provide valuable early indications of problem areas. Where applicable, traffic managers could utilize active control strategies (e.g., ramp metering to optimize flow) to mitigate problems.

Similar to wiper usage, ABS and/or vehicle stability control probe data could be used to alert traffic and incident managers of slippery road conditions. This information could be also used to notify the public via Variable Message Signs (VMS), Highway Advisory Radio (HAR) and DOT Internet sites that conditions are deteriorating.

7.4.3 Summer Maintenance

Summer maintenance activities such as pavement maintenance, pesticide spraying, road striping, and mowing are sensitive to extreme heat, high pavement temperatures, strong winds, and precipitation. Vehicle data can be used directly or integrated with other datasets as described previously to improve weather and road condition products for these end users.

Vehicle probe data of air temperature coupled with humidity data from RWIS or other surface observational data sources could be used to calculate local heat index temperatures, and to alert summer maintenance staff of unsafe conditions. Pavement temperature data measured by vehicles could be used to support striping operations. Wiper setting data could be used directly to identify road segments experiencing precipitation and to adjust mowing and pavement maintenance operations.

7.4.4 Emergency Management and Homeland Security

The current lack of a dense weather surface observation network presents significant challenges to emergency response personnel responding to hazardous chemical and/or biological releases. First responders typically obtain wind and stability information from local NWS observation sites, which can be many miles away. Wind and atmospheric stability can vary dramatically over just a few hundred feet. Local obstructions can influence wind flow and urban effects such as the heat island effect can have dramatic impacts on lower atmospheric stability, which is a critical parameter for predicting the flow and dissipation of hazardous plumes.

VII data can contribute valuable information in both rural regions and urban corridors. Dense observations of pressure and temperature from vehicles could be combined with radar and other local observations to initialize plume dispersion models. The high density of vehicle probe data in urban areas would provide critical environmental information that is generally lacking in the middle of cities. Local building effects on street level temperatures could be used to refine heat flux calculations in computational fluid dynamics models, which are now being used in research environments to study the flow in and around buildings in dense urban areas. In the next 10-20 years, these models will likely be used operationally to support emergency response operations. VII data will provide important input to these models.

Figure 7.16 illustrates the output from an urban scale plume model. Concentration levels are shown for a generic chemical being released from a single source. The general flow indicates that the hazardous plume will move toward the north through the urban corridor. Flow complexities in and around buildings are not shown in this diagram, but on the finest scales, concentration levels vary significantly from one city block to another in the center of the plume.

Vehicle data in and around the city could be used to refine stability measurements and support calculations to determine if the plume will mix with non-contaminated air through turbulence diffusion or have more laminar characteristics. Vehicle location information could be used to support evacuation decisions, as emergency response personnel would be able to view both the plume data and vehicle location data. Vehicles in harms way could be identified and notified to evacuate and be provided with guidance.

VII technologies could also be used to detect hazardous releases. Emergency personnel in Harris County, Texas instrumented a fleet of emergency vehicles (primarily police vehicles) with chemical detectors. For the year 2005 field test, they used carbon dioxide detectors. The objective of the experiment was to determine if the vehicles could be used to detect hazards and if so, could the information be communicated in near real time. The test was successful as the vehicle detectors were able to detect and transmit concentration information to the emergency management personnel. Local data were also used as input into a regional scale plume model, which was used to provide guidance to first responders. It is clear from the experiment that the operational concept was valid and this approach could be expanded nationally.

The instrumentation of fleets with supplemental weather sensors such as wind, humidity, and chemical sensors, would also provide critical input to plume models and could be used directly by emergency personnel to guide evacuation operations.

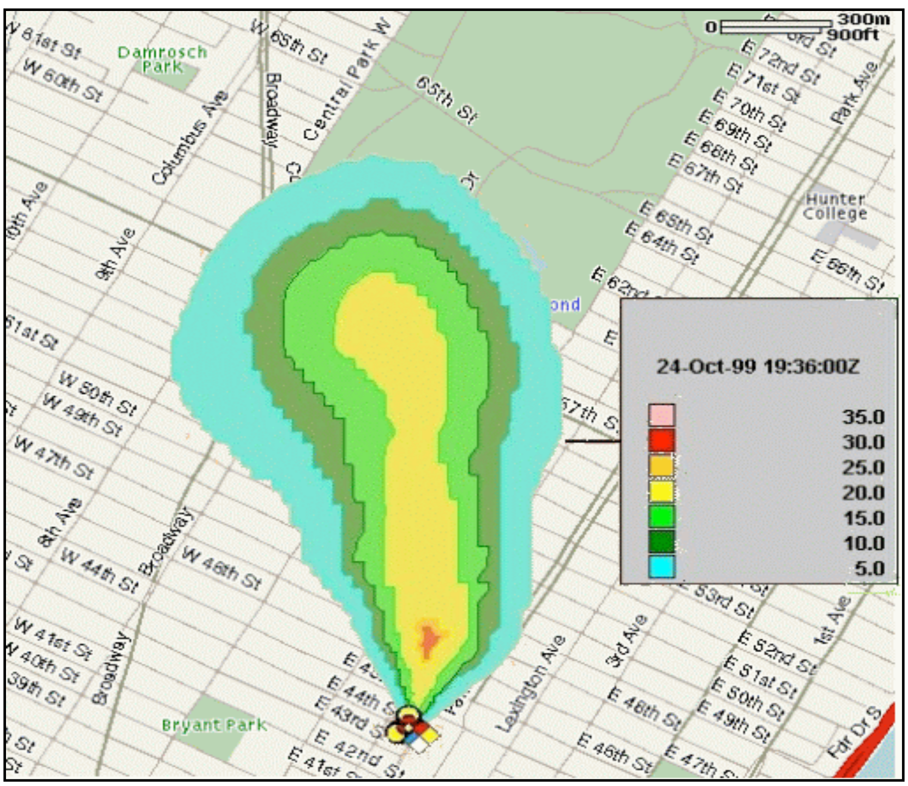

Figure 7.16. Output from an urban-scale plume dispersion model in an urban setting. Concentration levels are shown for a generic chemical released from a single source.

Key Points:

The number of road weather product enhancements and capabilities enabled by VII will be considerable. The accessibility of mobile data will benefit weather and pavement condition applications and products, as well as support transportation decision makers. As a result, several surface transportation stakeholder communities (traffic management, incident management, summer and winter maintenance, travelers, and emergency management) will profit from new and improved decision support products and tools.

The utilization of VII-enabled data will not be without its challenges. Data quality and data representativeness are some of the leading issues in terms of effectively exploiting these data. Additionally, uncertainties in the way vehicle operators interact with and use onboard systems is another concern. These issues and concerns will likely be addressed through comprehensive research and field operational testing.

VII will not only provide a way to acquire weather-related mobile data, but it will also serve as a means to deliver weather and road condition information to vehicle operators. This information could be provided to drivers in text, graphic, or audible formats. Such information would allow operators to make informed decisions regarding vehicle operation and course selection, which would improve roadway safety, mobility and efficiency.

8. VII Weather Data Processing

THE WEATHER DATA TRANSLATOR: FILTERING, QUALITY CHECKING, AND PROCESSING VII DATA

VII-enabled data are complex and pose a significant challenge, particularly when it comes to measuring or deriving weather and road condition data. Data issues include:

- Data volume
- Timeliness

- Quality
- Representativeness
- Format

These issues are not dissimilar to those associated with other fixed meteorological datasets, but the complexities are compounded by the fact that end users will have little knowledge about the source of the data. The NWS, FAA and other traditional providers of weather data follow stringent guidelines for instrumentation accuracy, precision, and siting. Other non-standard sources of meteorological data (e.g., Mesowest, local mesonetworks, school networks, hydrological networks, etc.) have existed for years, but have not been fully accepted or adopted by many end users including meteorological service providers because of ongoing concerns over data quality.

There is a well-founded belief in the meteorological community that "bad data is worse than no data." End users have demonstrated that they need to be very comfortable with data quality before they will utilize new datasets. What does this mean for VII-enabled weather and road condition data? It is clear that it will take a significant amount of research and outreach to demonstrate that VII-enabled data are of sufficient quality to be used for operational purposes. The uncertainties and complexity associated with raw VII-enabled data (unprocessed data from vehicles) will likely deter many end users from using the data. It is likely that most end users will not be able to handle the shear volume of VII-enabled data, let alone deal with data quality questions.

It is anticipated that many, if not most, users of VII-enabled weather data will require *processed* data. In this context, *processed* data means vehicle data that are extracted from the VII network, quality checked, and disseminated to active data subscribers. It is also likely that, due to the volume of data, many users will prefer statistically derived data representing specific geographical areas or times.

8.1 Weather Data Translator (WDT)

The concept of a VII weather and road condition data processor (a.k.a Weather Data Translator) has been discussed in both *Clarus* and VII Program meetings over the last year. In the view of the authors of this document, not only is the concept sound, *but the need for such a function is critical*.

In a fully functional VII-enabled environment, millions of vehicles will be acting as probes and will continuously send reports to the VII data network. Data subscribers will obtain the data they desire and use them for various applications. For many potential end users of the data, the volume of data will be overwhelming. Applications (middleware) that will facilitate the use of VII data will need to be implemented. Without such a function, the feasibility of utilizing vehicle probe data will be lower and there will be substantially more risk in its use.

The function of the proposed WDT is to extract data elements needed to derive weather and road condition information from the VII data network, filter the data to remove samples that are likely to be unrepresentative, quality check the data utilizing other local surface observations and ancillary datasets, generate statistical output for specific areas and time periods, and disseminate the quality-checked and statistically processed data to data subscribers, which may include other data processing and dissemination systems such as the *Clarus* System.

A conceptual illustration of the primary processing components of the proposed WDT is shown in Figure 8.1. Data from VII-enabled vehicles is communicated to the RSEs when the vehicles are within range of the receivers. The RSEs are connected to the VII telecommunications network where most VII data will flow.

The proposed WDT will include a data parser function that will extract weather and road condition relevant vehicle probe data from the VII network. The data elements selected for extraction will be determined by research results and feedback from the stakeholders. Data elements could be added or subtracted as needs vary. The data flowing out of the data parser is still considered ‘raw’ as it has not been processed in any way.

Data filtering algorithms could be applied to chosen data elements to remove data that are not likely to be representative of the true conditions. For example, research conducted by Mitretek *(13)* indicated that, in general, outside air temperature data are not representative of the true ambient conditions unless the vehicle speed is at least 25 mph. It was also found that the speed threshold is highly dependent on the location of the temperature sensors. Temperature sensors in the front bumper were more representative on average than sensors in other locations (e.g., under the hood). A test could be applied to the vehicle data to throw out all outside air temperature data measured when the vehicle speed was less than 25 mph. If information on the make and model of vehicle were available, the speed threshold could be specific to the vehicle (assuming that the vehicle information could be used to determine the location of the air temperature sensor).

Filters could also be applied to data sensed at particular locations that are known to generate errors (e.g., data measurements from inside tunnels). The process of deciding when and how to filter data will need to be done with great care, as one would not want to remove data that may have some use.

A benefit of filtering data that is considered unrepresentative is that the filtering procedure will reduce the amount of data that will need to undergo more complex and, in some cases, computationally intensive quality checking procedures. The WDT processor will need to be sufficiently capable to parse, filter, and quality check the data with minimal latency. Estimates of the computational requirements for the WDT are discussed in section 8.2.

Data that ‘pass’ the data filtering step will be quality checked where appropriate. Quality checking tests will include many of the common tests that are applied to surface weather data and more complex tests to handle road condition data. It is proposed that the quality checking tests being developed for the *Clarus* system be considered for the WDT for like data elements with appropriate modifications to deal with mobile data issues and idiosyncrasies. Ancillary data will be required to conduct many of the quality tests. Ancillary data will likely include surface weather observations and analyses, satellite, radar, and climatological data, and model output statistics. Data quality flags will be applied to the raw vehicle data so that data subscribers will have the flexibility of utilizing the raw data or taking advantage of the quality checking flags. It may not be possible or appropriate to quality check many of the data elements. For example, ABS status indicates whether the ABS is activated or not. There may not be an appropriate quality checking test that can be applied to these data within the WDT. How the data are ultimately utilized by downstream applications will be determined by data subscribers.

One branch of the quality checked data will flow (stream) to the output queue to minimize data latency. A second branch (a subset of the full dataset) will be cached and processed to generate statistical values for given locations (grid cell and/or point) and time periods. The statistical processing should result in a more representative sample and reduce the overall data load for users that cannot handle or do not need the streaming data from individual vehicles. It is envisioned that many downstream applications will only need data on a regular grid or data representing specific time periods.

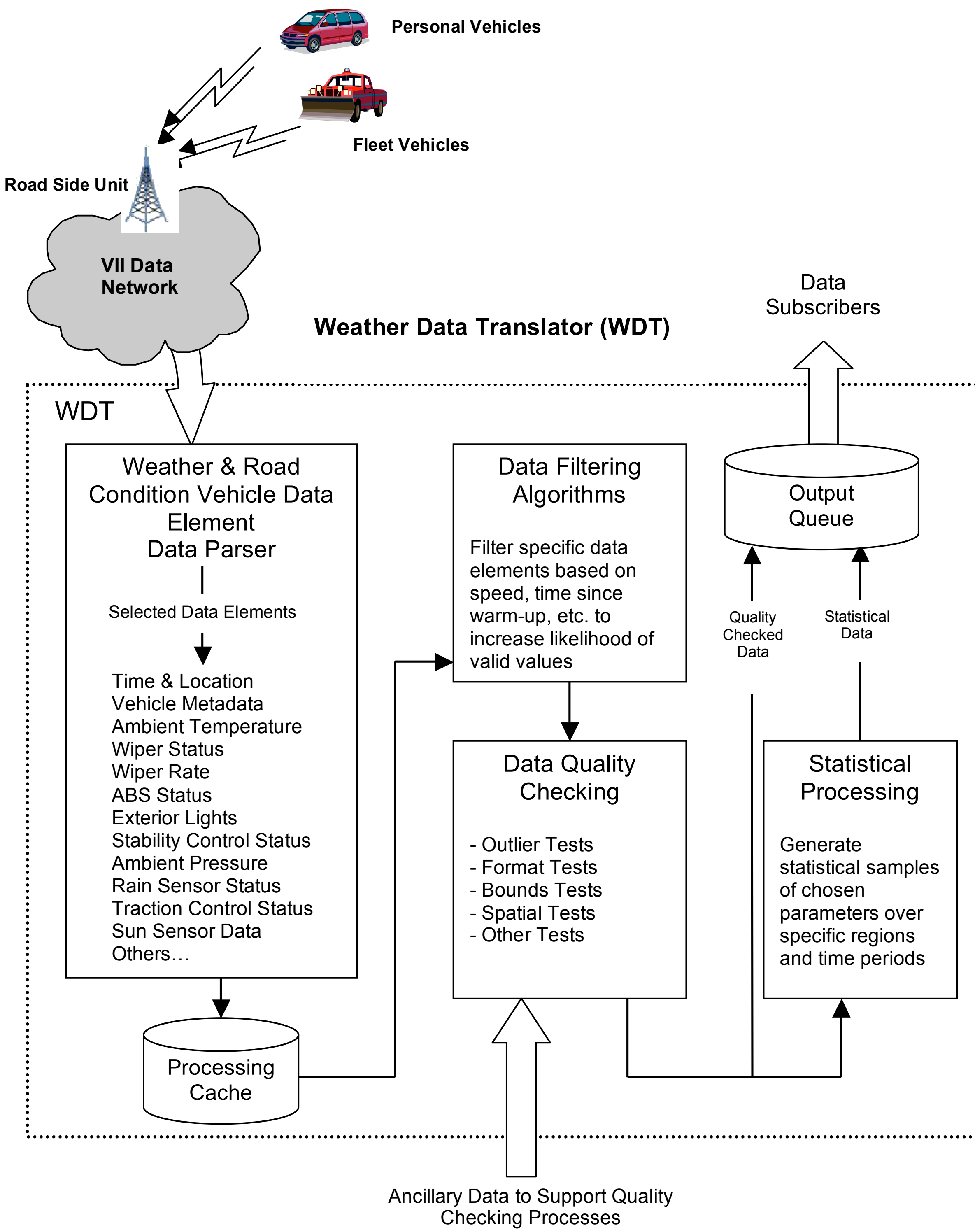

FIGURE 8.1. Conceptual illustration of the VII Weather Data Translator (WDT).

Research will be required to fully design, develop, and test the statistical processing component of the WDT. As a starting point, it is proposed that a regular grid with 2 km spacing be overlaid on the transportation network. Vehicle data that fall within the grid cells will accumulate over a period of 5 to 15 minutes and then be statistically processed. Data that can be arithmetically combined (e.g., air temperature, pressure) will be processed in that manner while system status data (e.g., wiper status) can be processed to generate information on event density, such as the number of events per grid cell per time period.

Output from the statistical data stream should be processed on a fixed temporal cycle and will need to include metrics that indicate the average, median, number of samples in the calculation, standard deviation, etc. The resulting capability, like the remainder of the WDT will need to be flexible and extensible to adapt to the changing VII environment.

It is strongly recommended that the methods and techniques utilized by the WDT remain non-proprietary and open for review and discussion. It is very likely that end users will be unwilling to utilize the data if there is a lack of knowledge or understanding of the processing techniques. The WDT should be designed to provide a single national conduit for VII-related weather and road condition data. This concept does not rule out a distributed computational capability, but, like the *Clarus* System, end users will likely demand a single interface for the data.

8.2 WDT Processing Requirements

The shear volume of data flowing through the VII system will require a network with substantial bandwidth and computational capacity to ensure that latency will not become a barrier to its use. Like the Internet, the technical capabilities, number of users, and applications of the system will expand with time. The design of the WDT will have to take into account the evolution of the VII network and be extensible to handle growing needs. Computer and network capabilities have consistently expanded over the last twenty years and this trend is expected to continue. The relatively slow implementation and adoption of VII across the nation will allow both VII data processing hardware and software systems to be adapted as the system evolves.

In this section, an attempt is made to estimate the computation requirements of the WDT. Several simplifying assumptions are made to constrain the problem including the following:

- Input and output streams are not compressed.
- Input and output record size of 40 bytes and 50 bytes, respectively.
- Data archive files on disk are not compressed.
- Data flowing into the WDT has been parsed to include only weather-related data elements. See Appendix C for a list of elements used in this exercise.
- Only weather-related data elements are processed.
- Statistical processing is done on a 2 km X 2 km grid covering the contiguous U.S. One representative value for each grid cell and each weather-related data element is computed every 15 minutes.
- WDT output includes both raw vehicle data with quality checking flags and statistically processed gridded data.
- Ancillary data used in statistical processing includes:
    - Surface observations
    - Radar data
    - Satellite data
    - Monthly climatology
    - Model output statistics
- Five basic quality checking tests are performed on each data element:
    - Format
    - Outlier
    - Bounds
    - Climate
    - Barnes spatial
- Periodic snapshots from 1 million vehicles are processed.
- Rural data rate – one record every 20 seconds from each vehicle.
- Urban data rate – one record every 4 seconds from each vehicle.

Given these assumptions, for periodic data coming from 1 million vehicles operating in a rural area, a computer node with two 3 gigahertz (GHz) dual core processors with 4 megabytes (MB) of cache, 6 gigabytes (GB) of memory, 600 GB of disk space, and two 100 megabit (Mbit) Ethernet cards would be required. The cost of this hardware would be about $6000. Data input into the WDT would average 2 megabytes per second (MB/s), and quality checked output would be on the order of 2.5 MB/s. Gridded output would be approximately 351 MB per hour. It would require 432 GB of disk space to keep a two-day archive of weather-related vehicle data including quality checking flags; a two-day archive of gridded data would require 16.8 GB of disk space.

To process urban data from 1 million vehicles, the minimal hardware requirements would include a computer node complete with two 3 GHz dual core processors with 4 MB of cache, 16 GB of memory, 2.5 terabytes (TB) of disk space, and three to four 100 Mbit Ethernet cards. The input data rate would average 10 MB/s, while quality checked output data would be roughly 12.5 MB/s. The amount of gridded data generated every hour would remain the same at 351 MB; however, it would require 11.25 GB of memory to handle the data processing needs compared to 2.25 GB for the rural case. The hardware cost for a system with these characteristics is estimated at $9000.

Ancillary data used in the quality checking process would require a single node consisting of two 3 GHz dual core processors with 4 MB of cache, 16 GB of memory, 1.5 TB of storage capacity, and a 100 Mbit Ethernet card. Presently, the approximate price of this system would be about $8000.

The estimated hardware specifications, data rates, and storage requirements are supplied here in an effort to give the reader a sense of what would be needed to effectively process weather-related VII-enabled data using a WDT. These estimates are based on several assumptions. Although all of these assumptions have an impact on the estimates, two are very central in terms of the amount of data processed in the WDT. The first is that data originate from 1 million vehicles in rural or urban environments. It should be noted that in the U.S. there are roughly 245 million registered vehicles[10]. As VII-related technologies are deployed and implemented, it is clear that the data flowing through the VII network will originate from more than 1 million vehicles. The second is that the WDT input data will include only weather-related elements, which will not be the case. The WDT will have to parse raw records (snapshots) before doing any quality checking or statistical processing. This would mean that the size of input data records would be significantly larger. Increases in data volume can be handled by adding additional nodes.

The amount of data produced by vehicles in a mature VII environment will be considerable; however, a gradual deployment of VII is anticipated. As a result, computer storage capacity, memory, and processing speeds will likely be able to keep pace with the growth and development of VII. The main factors that may constrain the use of VII-enabled data are network and device I/O (input/output). Testing using simulated data from 10 million vehicles revealed that the time needed for disk I/O (roughly 7-8 minutes) was 3 to 4 times that required for gridded data processing and quality control. As more and more vehicle data are generated, the capacity needed to acquire, distribute, read, and write data will increase.

[10] http://www.bts.gov (Bureau of Transportation Statistics)

Key Points:

The quantity of data that will result from VII deployment and implementation will be immense; in addition, the data quality will vary considerably. These factors could potentially overwhelm many prospective end users.

Techniques and methods that will facilitate the use of VII data should be explored and implemented. One such application that has been proposed herein is the Weather Data Translator, an algorithm-based software application designed to extract weather-related data elements from the VII data stream, remove unrepresentative elements, quality check data, generate statistical output, and disseminate data to end users or other data systems such as *Clarus*. End users that desire raw, unprocessed probe data would still be able to access those data.

WDT processed data will increase the feasibility of utilizing vehicle probe data as well as reduce the risks and uncertainties associated with using these data.

Developing a WDT to process VII-enabled data is viable using present day computational capabilities.

9. Extracting Intelligent Information From VII Data

DATA FUSION, DATA ASSIMILATION, AND EXPERT SYSTEMS

Meteorologists attempt to utilize all of the relevant information at their disposal to analyze current atmospheric conditions and formulate predictions of the weather. Over time, each develops a wealth of experience and knowledge regarding the strengths and weaknesses of various datasets and products. Moreover, they use well-developed subjective techniques and rules of thumb to combine information from disparate sources to achieve the optimum analysis or forecast. Forecasters who are regarded as experts in the field have improved their accuracy and skill over time by learning from their experiences.

In recent years, forecasters have been presented with a plethora of datasets and products. Although each of these resources has the potential to contribute vital information about the current and future state of the atmosphere, the process of examining and analyzing each of these components can be overwhelming, and in many cases, a forecaster must limit him or herself to a core group of products. The meteorological community has recognized this fact, and has made an effort to utilize intelligent system approaches to perform data analysis, data integration, product construction, and verification. The ultimate goal of an intelligent or "expert" system is to perform at the level of a human expert by leveraging knowledge and experience that has been gained over time.

9.1 Data Fusion

VII will provide new datasets that can contribute to expert systems, but at the same time, it will be a complex dataset that will have very distinctive characteristics. It is unlikely that VII data will be able to be used alone to make determinations about weather or road conditions; thus, there will likely be a need to explore techniques that integrate VII data with other weather-related datasets. The use of expert systems may be one method by which VII data can be combined with other datasets.

There are several types of experts systems: rule-based, fuzzy logic, frame-based, neural networks, and hybrids *(22)*. Much of the progress associated with advanced weather system design has been achieved by implementing fuzzy logic (continuous set theory) as the core mathematical foundation; however, the final system design is typically a combination of intelligent technologies (i.e. a hybrid expert system).

Classic Boolean logic, which is two-valued, draws upon well-defined, concrete categories (sets) to solve problems and answer questions. For example, consider the following statement:

"It is hot outside"

Boolean logic can only evaluate this statement in one of two ways: true or false. This is illustrated in Figure 9.1, with the red line (crisp set) demonstrating that the degree of membership (degree of truth) can only be 0 or 1. Note that because Boolean logic is two-valued, it cannot be used to characterize ambiguous concepts or solve nebulous problems. In contrast, the strength of fuzzy logic is the idea of multi-valued degrees of membership *(22)*. The fuzzy set displayed in Figure 9.1 shows that the degree of membership can range from 0 to 1 (green line), which alleviates the need to set thresholds too early in the process (i.e. using 80^{o}F as a breakpoint between not hot and hot).

As a result, an expert system can be designed to problem solve in the same manner as a human does, by combining heterogeneous datasets with differing levels of uncertainty to answer a question. This concept could be extremely powerful in terms of fusing VII data with ancillary datasets to construct road weather products.

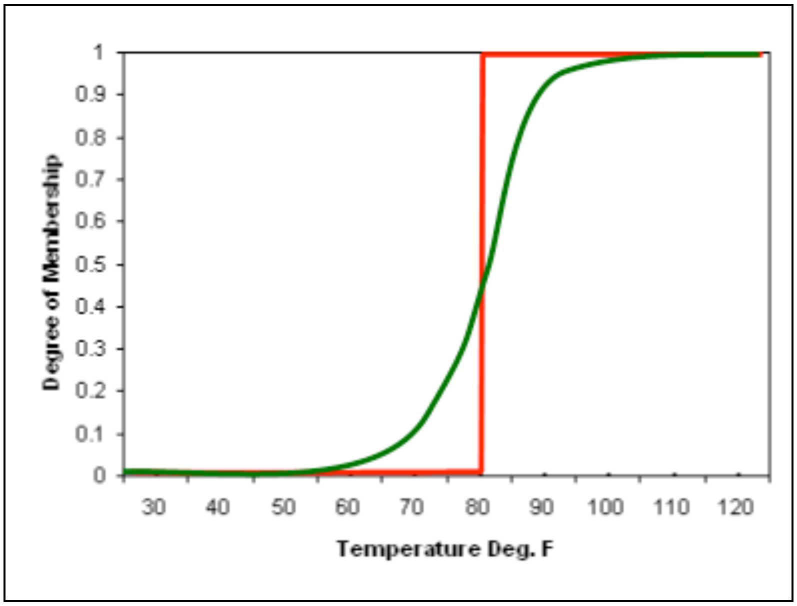

FIGURE 9.1. Crisp (red line) and fuzzy (green line) sets of "hot outside".

The process of diagnosing and forecasting weather-related hazards for all modes of transportation is beset with numerous challenges, with each mode offering its own set of unique issues. The lack of consistently accurate road weather hazard products is the result of several factors, some of which are noted below.

- Knowing the current and future state of weather and road conditions is dependent in part on having an extensive network of near surface observations. Many weather-related applications that target surface weather rely upon the national ASOS/AWOS network of observations. These observations are not generally located along roadways, and some of the data produced by these stations are not representative of near surface conditions (i.e. within a few feet of the surface). The deployment of road weather information systems (RWIS) has helped this issue, but the number of RWIS varies significantly from state to state, and the quality of data produced by some RWIS remains questionable due to the lack of uniform sensor maintenance and siting practices.

- A thorough understanding of the physical mechanisms that are responsible for road weather hazards is currently lacking. For instance, one atmospheric phenomenon that has been responsible for numerous fatal multi-car pileups along the nation's roadways is fog. Although the conditions commonly associated with fog have been identified, a substantial amount of research is still necessary to understand fully the physical processes associated with the formation, maintenance and dissipation of fog.
- Although there have been noteworthy advancements in the area of atmospheric numerical modeling, the ability of models to accurately resolve clouds and precipitation is limited. These elements are extremely important for highway safety and mobility. Dedicated research focused on these aspects of numerical modeling is currently being conducted, but it may be some years before models are able to consistently provide accurate, timely analyses and forecasts of precipitation intensity, location, and type.

These deficiencies reinforce the need to utilize data fusion techniques, such as those used in some expert systems, to integrate VII datasets with supplemental data to develop road weather products. Such techniques and systems are designed to take advantage of the strengths of various inputs (e.g. VII data, ASOS observations, model data, etc.) while minimizing the impact of their weaknesses. Moreover, these techniques can facilitate the fusing of large quantities of data to produce output that can be easily interpreted by end users or readily incorporated into other applications.

Section 6 illustrated the fact that weather-related vehicle data is highly correlated with supplementary data such as radar data and surface observations. Figure 9.2 shows a schematic of a data fusion product that includes VII data along with ancillary data. This product uses observations of wiper state, remotely sensed data, and supplemental surface observations (e.g. NWS ASOS stations) to diagnosis the location of heavy precipitation and its relation to major roadways. Each of the selected datasets is considered to have the ability to contribute some level of intelligence regarding the location of heavy precipitation in the region. For example, heavy precipitation is likely to be well correlated with VII wiper state reports of "high"; therefore, numerous reports of high wiper settings within a distinct area will increase the level of confidence that heavy precipitation is occurring in that area. Each dataset is mapped to an interest field using a fuzzy logic function. These functions are typically defined by human experts that have extensive experience with each dataset. Each of the resulting interest fields are normalized from 0 to 1, which simplifies the process of combining disparate data. Weights are applied to each of the normalized interest fields prior to combining the data. In some systems, these weights remain static, and in others, the weights can change each time the system executes.

Figure 9.2 illustrates a dynamic system where the weights are automatically adjusted based on validation of the inputs. In either case, the weights must be initially determined by a human expert. In this example algorithm, it is likely that radar data would initially receive the highest weight given that radar data generally do a good job identifying locations of heavy precipitation. In addition, radar data have been used for some time, and a considerable knowledge base has been built concerning the strengths and weaknesses of the data. As experience with VII data grows, the potential contribution of VII data in road weather applications will become clearer. In the heavy precipitation scenario, it is very plausible that wiper state data would be given the second highest weighting in the system since there is a direct relationship between heavy precipitation and wiper state. The final product shows which major roadways in the region are most impacted by heavy precipitation at the time the algorithm is run. This product uses a red, yellow, green color sequence to denote roads that are heavily impacted, moderately impacted, and unaffected, respectively.

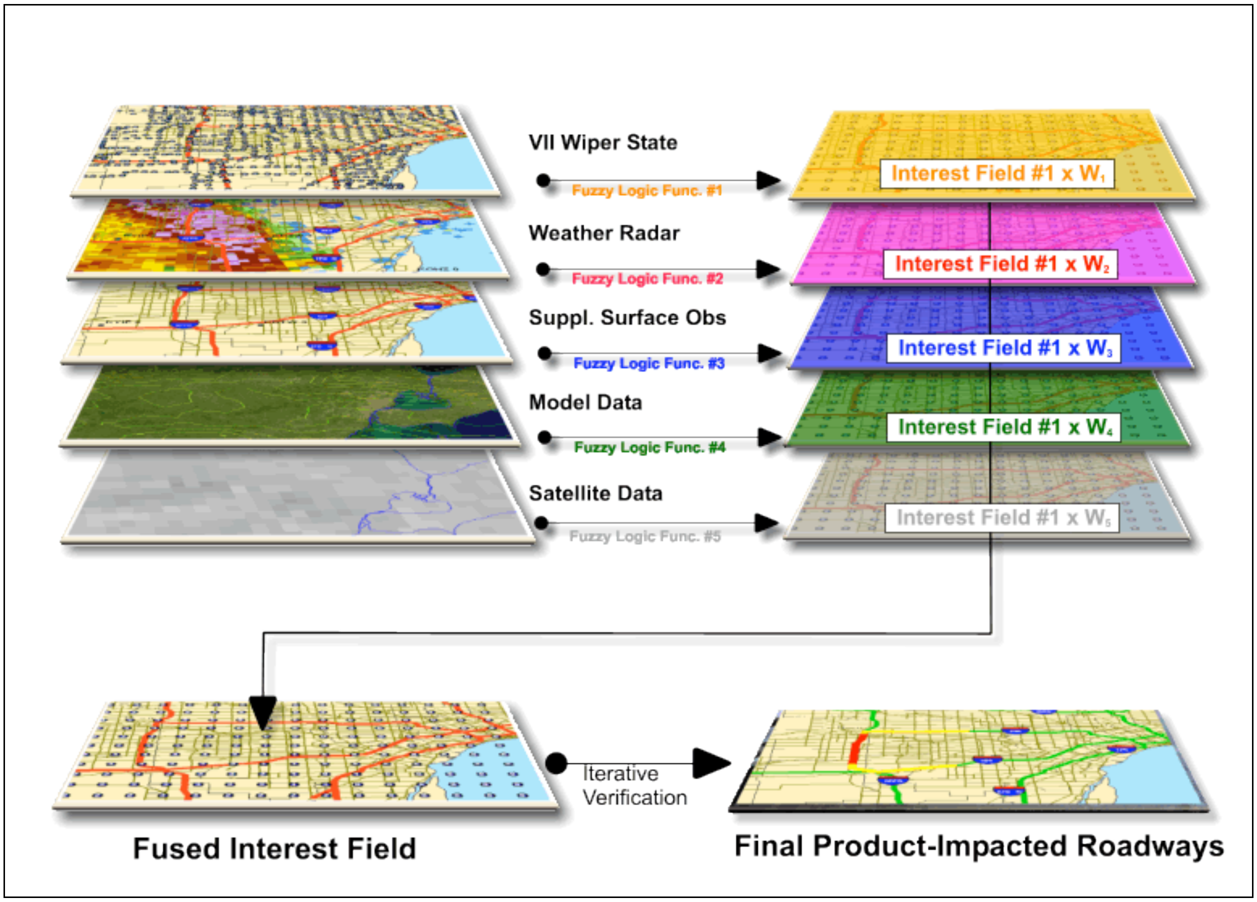

FIGURE 9.2. Schematic of a "heavy precipitation" fuzzy logic algorithm that utilizes VII data, radar data, model data, satellite data, and supplemental surface observations.

The example displayed in Figure 9.3 illustrates the use of VII data in the diagnosis of slippery pavement conditions. This product can be used in decision support systems that help to provide guidance for winter maintenance operations. Maintenance managers and crews can quickly identify the locations where they should focus additional resources. ABS information is the most critical element of the algorithm, as clusters of positive ABS events may be able to aid in pinpointing roadway segments that require the attention of maintenance crews. Note that more than one VII parameter could be used in the same application. In this case, vehicle speeds derived from VII data could be useful in determining areas where traffic speeds have been substantially degraded due to hazardous road conditions. Multiple ABS events may be correlated with decreases in average vehicle speed along a segment of roadway. Much like the previous example, several ABS events within a well-defined area would be required before the algorithm indicates slippery conditions. Additionally, slippery conditions inferred by ABS events would need to be supported by other data inputs. Since there is minimal experience using VII data, a considerable amount of research will be necessary to define the best practices for utilizing these data.

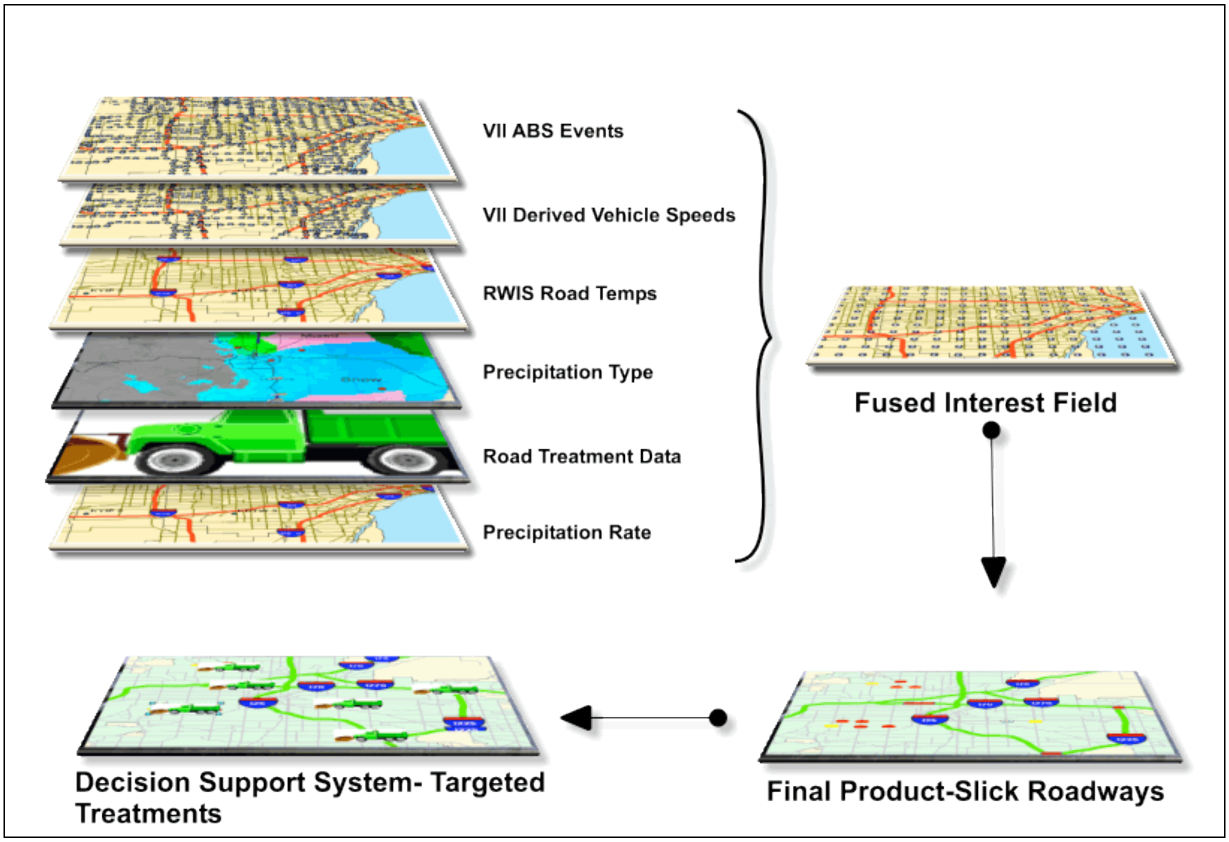

FIGURE 9.3. Representation of a data fusion algorithm for slick roadways.

9.2 Assimilating VII Data

VII-enabled data not only could be used directly as input into expert systems, but they could also contribute to other system inputs. Many expert systems rely on numerical model nowcasts and forecasts to produce optimized diagnoses and predictions of the atmosphere. As with other system inputs, an expert system attempts to maximize its performance by weighting model inputs based on their past performance. A numerical model's capacity to correctly predict the future state of the atmosphere is heavily reliant on accurately assessing the initial conditions. Numerical models use assimilation techniques to gather and process observations to evaluate the atmospheric conditions at t=0; however, the level of accuracy is related to the assimilation technique and the availability of observations.

Assimilating weather-related data enabled by VII into numerical models would improve model analyses and forecasts. A High-Resolution Land Data Assimilation System (HRLDAS) has been designed to simulate fine-scale soil moisture and temperature fields, surface sensible and latent heat fluxes, surface runoff, and water table recharge for use in mesoscale models *(23)*. VII would provide additional information about two of the most important forcing conditions used in HRLDAS: precipitation and solar radiation. In turn, improved output from HRLDAS would enhance road weather analyses and forecasts produced by mesoscale models.

Another data assimilation technique that has been shown to improve mesoscale (10s to 100s of km scales) and miso-scale (40 m to 4 km scales) model forecasts is the Real-Time Four Dimensional Data Assimilation (RTFDDA) system developed by NCAR and the Army Test and Evaluation Command (ATEC). The system incorporates real-time observations into a continually running data assimilation system. Each real-time observation is weighted based upon the time and location of the observation *(24)*. Currently, the RTFDDA ingests data for a number of sources, but surface observations are limited to hourly reports and regional mesonets. Again, VII would supply additional high-resolution data to assimilation systems such as the RTFDDA system, facilitating improvements in road weather products.

Finally, an ensemble Kalman filter assimilation system with one dimensional column domains has been used successfully to generate a virtual boundary layer profiler network from surface observations alone (25). The inputs to this system include surface observations of temperature, winds and water vapor. Although vehicles are presently only capable of supplying temperature observations to this system, future automotive advancements may result in the availability of atmospheric moisture and wind information (speed and direction), which in turn, would provide a voluminous dataset for this technique.

Key Points:

It is unlikely that VII-enabled weather-related data elements will be able to stand alone as truth. The most effective method of exploiting VII weather and road condition data will be to combine the data with conventional datasets such as nearby stationary surface observations or remotely sensed data.

Data fusion has been used by the weather community for numerous years to extract and combine information from disparate datasets. These techniques, which attempt to take advantage of a dataset's strengths while minimizing the impact of its weaknesses, have been used in many expert weather systems. Weather applications and products that attempt to use VII-enabled data should take advantage of data fusion techniques.

The accuracy of weather forecasts produced by numerical models is highly dependent in part upon the model's ability to correctly assess the initial state of the atmosphere. Such models use data assimilation techniques to gather information concerning the current conditions; however, the amount of available data, especially near surface, is limited. VII will provide data that can help to fill existing gaps, which will result in improved weather forecasts.

10. Overview of Research Needs

REQUIREMENTS FOR MAKING EFFECTIVE USE OF VII DATA FOR ENHANCING ROAD WEATHER INFORMATION

VII will support the development of weather-related products for the surface transportation community. However, it is evident that the use of VII-enabled data for product development and enhancement will also be beset with challenges. In order to make effective use of mobile data for weather-related applications, it will be necessary to invest in research to understand issues associated with current and anticipated data elements. This section of the paper discusses a sampling of VII-related research and development topics that are needed to support the development and improvement of weather and road condition related products.

10.1 Probe Message Processes

Data loss and data latency are critical areas of focus in analyzing probe message process alternatives. As discussed in section 4.2, VII probe message processes will have a critical impact on the development of VII applications. One vital aspect of the probe message processes that may have a considerable impact on weather-related applications is the method by which snapshots are generated and stored on each vehicle. Vehicle data most essential to some weather applications and algorithms will be associated with periodic snapshots. Periodic snapshots are considered to be of lower priority as compared to event and start/stop generated snapshots. In the case of a full buffer, periodic snapshots will be deleted in favor of other snapshots. Under some circumstances (e.g. heavy traffic), this characteristic will result in data loss on spatial and temporal scales necessary for some applications. Data latency may also be an issue related to data delivery via the VII network. Under the current VII framework, vehicles will be capable of storing snapshots that contain environmental and road condition data. The possibility of using some snapshots will depend on how often a vehicle comes within communication range of an RSE. To ensure the stability and accuracy of weather-related VII applications, research is required to examine, design, evaluate, and demonstrate the impact of probe message processes on applications under various conditions.

10.2 VII Adoption Rates

The deployment rate of VII technologies will determine how, when, and where applications can be developed and implemented. For most weather-related applications, there will be some minimum number of data points necessary to produce accurate, timely products. Below this threshold, the impact of VII data on weather and road condition algorithms or applications may be low. The deployment of VII will likely take place over a significant period, with initial deployment in urban areas followed by rural areas. Once the VII hardware is deployed, there will be a gradual increase in vehicle data uptake rates as more vehicles equipped with on-board units begin transmitting data to RSEs. Because of the probable variation in data density from region to region, research will be required to understand and document the amount of data that will be required to support various weather applications.

10.3 Data Processing

Appropriate sampling methods need to be defined in order effectively use VII data. A key advantage of VII is the amount of data that will be made available to support weather and road condition applications. However, this can also be seen as a disadvantage. As deployment of roadside and on-board equipment increases, the magnitude of vehicle data will also increase. It is not presently clear exactly how much data would flow through the VII network, but it will be sizeable. This may result in situations where there is excessive data within the domain of interest. Thus, VII research should include examining the use of statistical techniques to process large amounts of data. It may be found that it is possible to translate VII data into points, segments, grids, and profiles without losing information. This type of statistical processing would facilitate the use of large amounts of vehicle information in some algorithms and applications. Many of these issues will need to be addressed as part of the development process for the WDT.

10.4 Data Quality and Accuracy

The range of data quality and accuracy among various vehicles needs to be established to estimate error more effectively. In a recent study, air temperature observations were taken from mobile sensing platforms along a stretch of road west of the Washington D.C. area (Dulles toll road in Virginia). It was found that the observations were affected by sensor placement, traffic congestion, sun angle and the presence of precipitation. The study also noted that vehicles of the same make and model reported different temperatures under identical environmental and roadway conditions. Finally, a small bias was found in the air temperature observations *(8)*. This type of investigation points to the need for additional research on the quality and accuracy of vehicle generated data. The deployment of VII will result in vehicle data elements from various automobile manufacturers, vehicle types, sensor manufacturers, etc; therefore, it is important that research be conducted to evaluate data quality and accuracy issues associated with use of various vehicle data elements.

10.5 Quality Checking

Quality checking tests will be needed to filter anomalous data from faulty vehicle sensors. Stationary weather platforms such as the NWS ASOS stations are remotely monitored. These platforms also have some limited quality control algorithms designed into the system. Should a problem arise that cannot be fixed remotely, a technician can be dispatched to rectify the problem. In the case of vehicle data, it is unlikely that vehicle operators will have the capability to monitor the output for problems. Even when an issue is identified by an operator, it could be days or months before the vehicle is serviced, and the sensor or system linked to the problem returned to a normal operating state. For this reason (and others previously mentioned), the use of data quality checking procedures on VII data will be necessary to ensure the highest quality data possible. Research is needed to explore the types of quality checking procedures that could be implemented. This research may include investigating the use of current quality checking techniques on VII-enabled data, the use of ancillary data for quality checking, and the development of advanced techniques for mobile platforms.

10.6 Data Fusion

Research is required to investigate the most efficient and effective ways to combine data derived from vehicles with commonly used meteorological datasets such as ASOS, radar, numerical model, and satellite data. The utility and value of ingesting mobile data into other weather products should also be examined. In order to create weather-related applications utilizing VII-enabled data, it will be necessary to combine vehicle data with other complementary data sets using data fusion techniques. The temporal and spatial resolution of VII-enabled data will be a great deal higher than the majority of datasets presently available to the meteorological community. These characteristics would contribute to the identification of small-scale weather features, micro-climates, and localized road conditions; however, new data fusion techniques will need to be developed to take full advantage of VII data.

10.7 Numerical Weather Prediction Model Forecasts

The availability of VII-enabled data will enable improvements in the ability of numerical models to forecast changes in the atmosphere, including the atmospheric boundary layer. The ability of models to forecast accurate boundary layer conditions is dependent on four primary factors: the spatial resolution of the model, the effective simulation of dynamics at various scales, the parameterization scheme used to characterize surface and turbulent processes, and the accuracy of the initial atmospheric structure and surface parameters *(9)*. While the capacity of numerical models to forecast surface conditions is dependent on more than simply defining the initial state of the atmosphere, it is clear that accurate characterization of the atmosphere is an important component in the prediction process. Research is needed to explore the impact of VII data on weather model forecasts of the boundary layer, including data assimilation of mobile data, quality and quantity requirements, and the utilization of indirect atmospheric measurements (e.g. wiper state).

10.8 Human Factors

A number of anticipated weather and road product improvements resulting from VII-enabled data are based on indirect measurements of environmental and road conditions. An example would be the use of windshield wiper state to infer the presence or lack of precipitation. The way in which one person operates a vehicle will differ considerably from another. These differences could be attributed to a number of factors such as age, experience, vehicle, etc. Research is needed to investigate how various segments of the population use common vehicle systems (e.g. wipers, lights, brakes, etc.) during normal and adverse weather and road conditions. This information would be incorporated directly into algorithms and applications, and result in more accurate analyses and forecasts of road weather parameters.

> **Key Points:**
>
> A significant amount of research will be required to fully understand VII-enabled data and how best to use the data to diagnose and predict road weather hazards. Research needs to address, data characteristics, volume, quality, timeliness, and representativeness. In addition, research is required to understand how to best utilize valid VII data in the generation of new and improved weather and road condition products and how to tailor the products for various user categories (traffic, incident, and emergency management, maintenance, etc.).

11. Next Steps

RECOMMENDATIONS FOR MOVING FORWARD

The overarching goal of the VII initiative from a weather perspective is for the weather enterprise (defined as all the public and private organizations that collect, process, and generate weather products) to utilize vehicle data to improve weather and road condition products and to provide those products to transportation system decision makers including travelers.

The utilization of data from mobile platforms is not new in the weather community, as ship-based observations have been used for more than a century. Data from aircraft have been used successfully for nearly a decade, and the number of parameters available from aircraft is expanding from primarily wind and temperature to humidity, turbulence, and icing. The utilization of data from vehicles poses significant technical challenges, particularly with respect to data quality; nevertheless, VII represents a technology that holds considerable promise of significantly increasing the density of weather observations in the atmospheric boundary layer.

Case studies in which vehicle data were compared with conventional weather data were presented herein. These cases were promising; there was good correlation between vehicle data elements (wiper state, temperature, and pressure), radar data, and surrounding surface observations. Vehicle data acquisition and distribution enabled by VII will result in a number of road weather product improvements. Potentially, these improvements will include the ability to provide accurate, timely diagnoses and predictions of atmospheric and road conditions. This information could be distributed to surface transportation stakeholders, including vehicle operators, to improve roadway safety and mobility.

One of the most important aspects of VII in terms of weather application development is the fact that a significant amount of research will be required to understand the most effective methods of using vehicle-based data, as the characteristics of the data will vary greatly between vehicle manufacturers, vehicle models of the same manufacturer, and sensors types and models. It is unlikely that any single vehicle-based data element will be able to stand alone as truth, as there will be too many uncertainties about their quality. Vehicle data will need to be processed in a statistical manner to address data outliers and to raise the overall confidence in data quality. The weather community has substantial experience combining multiple disparate datasets to derive products. Vehicle data will have to be treated in a similar manner. Even with those caveats and concerns, the authors believe that it will be feasible to utilize VII-enabled vehicle probe data in the generation of weather and road condition products and that these new datasets will contribute to an improvement in roadway safety, mobility and efficiency.

In order to ensure the success of the VII initiative from a weather perspective, the authors recommend that several steps be taken. They include the following:

1. ***Experts from the meteorological community should take an active role in helping to guide selected aspects of the VII program such as the proposed strategies for RSE deployment and probe message processes, and the design and implementation of VII-related proof of concept and field operational tests***. It is clear that selected components of the VII program will have a substantial affect on how and what road weather products can be enhanced and developed using VII-enabled data. In addition, the validity of road weather products will be determined by the approaches used in the VII test and deployment process. Given that the weather community will likely be a key user of VII data, including weather experts in discussions regarding selected elements of the VII program will ensure that final system design will take into account road weather application needs.

2. ***A Weather Data Translator (WDT) should be developed and field tested to facilitate the use of weather-related vehicle probe data***. Once VII is fully deployed and implemented, thousands of vehicles will be routinely gathering and transmitting information to the VII network

for distribution to data subscribers. Many of these subscribers may not have the knowledge or capacity to use vehicle data in its “raw” form. A WDT will provide the necessary data processing (filtering, quality checking, and statistical processing) that will enable the use of VII data by a larger number of subscribers. Without such a function, the feasibility of utilizing vehicle probe data will be lower and there will be substantially more risk in its use. The WDT will require a significant amount of scientific and engineering research and development. The complexity of the WDT should not be underestimated.

3. ***Significant investments should be made in research and development that will support effective use of current and anticipated weather-related vehicle data elements***. It is apparent that the use of weather-related data elements for the improvement of road weather products will contain numerous scientific and technical challenges. Therefore, it is imperative that research be conducted to identify, understand, and if possible, resolve these issues. Research should include, but not be limited to, investigations into the impact of probe message processes and RSE deployment, VII adoption rates, data quality, quality checking for mobile platforms, data processing, human factors, data assimilation in numerical models, and data fusion techniques.

4. ***Application and product developers should refrain from attempting to use weather-related VII data elements as standalone truth***. Raw vehicle data elements will contain a considerable amount of uncertainty with regard to data quality and representativeness, but it is evident that, at some level, VII-enabled data will be able to provide information about the state of the atmosphere and road conditions. This information should be derived from VII and ancillary datasets by utilizing advanced data processing techniques.

5. ***It is essential that prior to product development, developers conduct extensive research on the vehicle data elements of interest in an effort to ensure the proper use of those data. If possible, this should include collaborating with multiple OEMs that design and implement the sensors or devices from which the data originate***. Although work is being done to construct a set of standards for VII data (e.g. data units, data precision, etc.), vehicle data are produced from onboard sensors and devices that originate from numerous OEMs and their subcontractors. Thus, it will be vital for weather and road condition product developers to gain a thorough understanding of

vehicle data. For example, traction control event data supplied by the VII network may inform a data user that an event occurred; however, the user will not have any information about how traction control was implemented on that particular vehicle (e.g. operational limits). Thus, it will be important for weather application developers to acquire a broad understanding of the characteristics associated with the vehicle data they are attempting to use.

6. ***The initial process of improving road weather information through VII should begin with targeting basic applications and products that can be improved or constructed with rudimentary vehicle data elements (e.g. temperature, pressure, and wiper state).*** This study has documented a number of potential data elements that could be used for road weather information purposes. However, it is vital that developers do not attempt to solve complex problems while VII is in its infancy. There is a considerable amount to learn regarding data acquisition, transmission, quality, etc. To attempt to use information such as millimeter-wave radar data before gaining a more thorough understanding of more basic elements like temperature could be detrimental to the success of VII, as it relates to potential weather and road condition related enhancements.

The potential use of VII-enabled data in weather and road condition-related applications and products for surface transportation has been examined herein. The availability of VII-enabled data would most certainly lead to improvements in road weather products. Advancements in the diagnosis and prediction of adverse weather and road conditions could be realized using data currently available from many vehicles. Moreover, technological improvements in the automotive industry will likely result in additional environmental and road-related data elements becoming available in the future, which will provide additional capability for improving and generating weather-related products for the surface transportation industry.

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Appendix A

VII Weather Applications Workshop I
Boulder, Colorado
Wednesday, February 22, 2006
Meeting Notes

NCAR, with support from the Federal Highway Administration, is investigating the possibilities of deriving weather and road condition information from vehicle data elements. The benefit is enabling tactical and strategic response to weather related surface transportation hazards. The objective is to produce a feasibility and concept development report for VII.

A presentation by the Federal Highway Administration (FHWA) on the VII Initiative and Day 1 Applications – The *Clarus* Initiative - was given, with discussion on the following topics: motivations for the Clarus Initiative, VII's impact on overcoming gaps and decision making, an overview of VII program activities, VII use case development, the purpose of use cases, an overview on VII program activities, use case development schedule, roadway environmental condition information, winter maintenance, traffic management (potholes), and roadway environmental condition information (traveler notification with and without *Clarus*).

Additional comments:

- The end result of this research is not data but rather relevant information, i.e. taking raw data, assigning relevance and then converting it to useful information. Some public data sets will be available; *Clarus* is much more focused. Data can be obtained from publicly owned assets and we are also working with many private entities. The operational entity to manage VII and to design the architecture is to be determined. Security is a big issue.
- A clear vision on how VII data is to be used is needed; the process could easily take a direction not intended. Privacy principles are a consideration. If VII is perceived as enforcement information it will more than likely not be accepted by the public.
- A set of data exists which can be transformed into benefits for society – this is the crux of the surface transportation program. We have an obligation to protect goods and people going from point A to point B within a reasonable time range. To accomplish that, we need data; the *Clarus* system manages that data.

A FHWA architecture overview was given on VII with emphasis on: the program overview, SDNs and NAPs, supporting a variety of network services or applications, providing data transport in support of both public and private services, vehicle probe data, vehicle probe data collection, and vehicle probe data distribution.

Additional comments:

- Commercial vehicles are likely to become the earliest users of VII. Each commercial user makes use of data in a different way and that may or may not include a standardized data bus. The controller area network is a challenge.
- A test bed is to be implemented by the end of April with the framework to be determined. Warning of severe weather occurrences, such as tornadoes, could potentially be of high significance to the customer. The common thread is what transpires longitudinally along the roadway surface.
- Vehicle sensors can fill in surface data gaps and help fine tune products. A greater number of observations will help the weather prediction effort. Upper air information can be obtained from aircraft. Related techniques in terms of data utilization could be use for VII and the surface transportation community.
- Regarding secure technology, there is concern about web traffic. There is also concern about how many RC's are going through the server; 250,000 come from the DOT. The VII system delivers public and private data through the network of SDN service routes and private services through NAPs. Roadside equipment was first used in urban areas to foster safety at intersections.

Discussions took place concerning the type and placement of sensors in Michigan and whether or not they can be taken to the level of RFP. There is currently a small network with capability to grow but that is uncertain at the present time. The citizen driver should be able to decide what options to use and that would be controlled. Three new processes are involved: 1. safety, 2. mobility and 3. commercial processes. Observations generally fall into 3 categories:1. public domain data, 2. probe data from vehicles in range of RSE and 3. public safety messages. Private data is confidential – encrypted. Vehicle probe data is constructed by the OBEs and will contain the following data: periodic data – snapshots, event data – traction control, anti lock brakes

Cost is a consideration for car companies. This is not meant to be an "all or nothing" scenario; the plan is to proceed slowly.

Discussion on communication between vehicles and a fixed infrastructure. User does not mean "driver" but "application."
RSE broadcasts every 100 milliseconds – RSE public message priorities are

1. Local safety applications
2. TOC advisory messages
3. OEM diagnostics and safety notices
4. Commercial services

A presentation on acquisition and utilization of vehicle data elements was given and the following areas were discussed: Use cases, Use case scenarios, VII OBE Hardware Architecture, Present OEM Traffic (Incident, Weather) Information Collaboration, Collect and Distribute Probe Data, Provide Off-Board Navigation, OBE hardware architecture, human machine interface, and the mechanism for collecting.

For the proof of concept, vehicles that can support the system will be designed and chosen - a fleet of about 100 vehicles fully equipped with all on board equipment. Design experiments will commence in the beginning of 2008 and last about a year. It will be available to automakers by approximately 2011; however these are very rough timeframes. It will be a difficult interaction to package weather information and set it up.

A presentation was made on vehicles as mobile sensing platforms for critical weather data and discussed were task objectives and timeline, collaboration with NCAR, the Dulles toll road instrumented corridor, sensors, test vehicles, sensor placement, sensor maintenance and calibration, data collection, mobile data samples, fixed sensors, the Dulles Airport ASOS, NWS Doppler radar, road domain translation to radar reference frame via GIS, precipitation estimates on road segments, establishing ground truth, temperature data time series, heavy traffic occurrences, average temperature statistics, average variation by sensor type, mobile versus in situ temperatures, proposed data comparisons and a deliverable report.

A presentation on Weather & Road Condition Product Improvements Enabled by Vehicle Infrastructure Integration included the following: data fusion – road weather impact products, weather improvements enabled by VII, radar based precipitation identification, diagnosis of precipitation type, identification of foggy regions, improved high resolution modeling, defining atmospheric vertical profiles, boundary layer characterization, road condition improvements enabled by VII (some examples), winter maintenance operations, road condition reporting, and surface temperature gradients.

Additional comments:

- VII enables tactical and strategic decisions to be made on how we drive our vehicles. The scale is large to small. The challenges lie in how data is conveyed to the community. Placement of sensors and sensor type can affect the quality and accuracy of the data. The problem in accounting for biases is vehicle knowledge and privacy. The suggestion is to stay on the conservative side, work with more data and get a sense for the numbers. VII has filled in gaps from point to point. Many of the data needs to be moved downstream to the network.
- An observation is simply just that - an observation. It is probably a mistake to try and average observations. We may need to do some data volume reduction – compression of data. Each sensor and observation is processed in a specific way depending on how data is to be used, i.e. wind.
- There is more accuracy collecting data from urban areas. Rural vehicles are typically not equipped to make applications work in all environments. The accident record for rural versus urban was noted; there are more fatalities in rural areas – speed is a factor.
- Privately owned vehicles are needed for spread of data. The reality is that most of the commercial companies have sensor capability but using commercial vehicles as high quality sensors, identifying sources of data, sharing is not feasible. A lot of traffic activity goes on between midnight and 6 a.m. and gaps need to be filled.

- VII would have provided differences in temperature between Denver proper and the mountain areas. In mountain areas, the number of observations would be increased.

DOTs would love to have access to information from the vehicles. Many data will be duplicated, some weather related and some not. The possibility exists for getting information related to blow-over phenomena moving with lateral force, such as high wind. Tornado prediction should be added. There is a target audience and a large emotional impact on the public. The data can also be used elsewhere. Predicting paths of tornadoes can be quite a challenge. The usefulness of information to the driver and cost considerations are at the forefront.

A second meeting is being planned, possibly at Chrysler Corporation, Detroit. An effort will be made to keep the group small.

Appendix B

VII Weather Applications Workshop I
Boulder, Colorado
Wednesday, June 21, 2006
Meeting Notes

This meeting focuses on new technology to determine where weather fits into the whole Vehicle Infrastructure Integration picture. The subject matter is problematic ranging from purely political to purely economical. We are focusing on the technical aspect but should be cognizant of the politics and economy; it is important that we know the constraints. An open and relaxed exchange of ideas is encouraged. We are in information-gathering mode and are anxious to hear what other people have to say. The number of opportunities and possibilities for VII are tremendous. The plan is to produce a VII weather applications feasibility report.

An ITS General overview presentation was given with focus on DOT vision for the VII initiative, the five phases of the Initiative, application development, Day-1 use cases, researching the data characteristics, key deliverables and outcomes of data characterization research, and building and testing applications.

Additional comments:

- Operators will benefit from the VII application for crash avoidance, the ultimate goal being to make driving safer. Pothole detection uses the same technology as some weather detection devices. The main thrust is near-term analytical emphasis on the support of Day 1 applications. Data uses can be "grown" using the tools we have, making them better and better.

A VII Consortium update presentation was given and included discussions on an overview of VIIC, near-term activities, the Proof of Concept test, contributions to weather information, probe data collection, probe data distribution, uses of weather information, an in-vehicle display application example, a navigation application example, development test environment for the west, central and east sections, and weather community participation

Additional comments:

- Any of the vehicle manufacturers can join. A cooperative agreement is in place between USDOT and VIIC. Ford, Nissan, BMW, Honda, DCX and VW are some of the manufacturers participating. VIIC concentrates on the physical elements installed in vehicles, and considers all vehicle equipment and applications. There will be a Proof of Concept test in 2007 with a fleet of 20 to 30 vehicles dedicated. Testing will begin with rudimentary data such as elevation, position, heading, time, speed, etc. and start with small amounts of information.

- VII takes in a wealth of information, and the primary purpose is to exercise the system, and its ability to do and not do certain things. Relevancy and human factors are not a part of this effort. The laying out work will take place after these exercises are completed. There are a number of engineering versus policy decisions to make. A proper balance between technology and privacy issues is necessary; in the public sector privacy needs to be taken into account.
- VII is already being used extensively, i.e. cell phones, etc. The premise is to choose a "dumb" on-board vehicle/"smart" off-board system; the on-board system can be informing the off-board of position. There will not be an ubiquitous connection from end to end - 2 environmental stations.
- An official VII test bed in California is working independently, and would be complimented by the NYC test bed. The issue of type of vehicles to use is being worked out, but probably heavy vehicles will not be used. Light trucks and vehicles are more likely candidates.

A VII system architecture overview was given and discussion included system architecture, VII system services and contact information. The system architecture chart was reviewed, as were national access points, and service delivery nodes.

A presentation on VII Probe message processes was given with emphasis on the intent, content, structure and header of probe messages, position and time, vehicle and weather status elements, the generation of snapshots, transmission, concept, examples and management of probe messages and current status.

Additional comments:

- Users of probe messages will be able to control how often and where to use information. It cannot be assumed that all cases have all elements, or that all data is coming from all cars. The data will be different from different manufacturers and numbers will be large, so items that are the same across the board should be selected. The intent is to connect to a consistent unit. Vehicles will be more consistent after the year 2012. Goals need to be attainable. Multiple data points, not just one, will be used to make a decision. The challenge is arbitration - deciding the appropriate time for messages.
- Periodic snapshots could be generated by distance alone, not speed. The owner of the road would be one of those who manage. Important snapshots could not be dropped. If there are no snapshots taken between stop and start, we know that it's because traffic is stopped or something is broken.

A presentation was given on the VII tasks, overview and update of data characteristics for traffic management and discussion focused on scope, objectives, staffing and coordination, approach, VII data characteristics task, key deliverables, the strengths and weaknesses of observed floating car and observed data sets, the strengths and weaknesses of simulated vehicle trajectories, a walk-through of the default VII probe message process, and preliminary observations and analysis.

Additional comments:

- Details such as spacing/deleting of snapshots, stops and starts, creep times and high congestion were discussed. The analytical process will be finalized in January.

A presentation on Weather Related VII Use Cases was given with focus on timeline, comment summary, primary changes, draft highly conceptual WDT, current status, improving weather observing and forecasting – *Clarus* drill-down and other USDOT Day 1 use cases

Additional comments:

- It's up to the operational entity to decide what the priorities will be.

A presentation was given on vehicles and mobile meteorological platforms with emphasis on distribution of ASOS observations, numbers, Mitretek research objectives, Mobile Wireless Laboratory (MoWL), sensor placement, test domains, vehicle platoon formation, data collection segments on the DTR, data synchronization and availability, single point data samples, data run history, DTR thermal profile (air temp), Question1 (Q1): data accuracy, Q2: temperature vs. vehicle speed, congestion modifying road temps, Q3: sensor placement, Q4: temp profiles of like vehicles, Q5: external weather effects, Manual Observations from the MoWL, External Effects, precipitation, and summary challenges.

Additional comments:

- The appropriateness of using probe data from passenger vehicles was discussed. The positioning of various probes on certain vehicles and its relationship to the types of data being collected is significant.

A presentation was given on human factors and VII-enabled applications with discussions including UMTRI, combining human factors and engineering domains of research, driver assistance systems research, origins of the naturalistic data, UMTRI naturalistic data with driver assistance systems, data acquisition and remote monitoring, recent FOT data scope, integrated data collection, data analysis and warehousing, video and visualization tools, overlaying vehicle data with crash and roadway data, naturalistic examination of windshield wiper usage, the data set, wiper utilization by month, wiper speed selection: ambient light level, naturalistic use of high-beam headlamps, high-beam usage, headlamp usage, results, naturalistic ABS events, the data set, ABS and precipitation/temperature, ABS and road class, ABS and speed, video samples, and the implications for VII weather.

Additional comments:

- Data is now ripe for mining, and there are heavily equipped fleets of vehicles with data acquisition systems in place. Wipers should not be a VII event even though wiper use can be modeled. Care needs to be taken to avoid using data improperly.
- Concerning the current state of the system, we do not know the initial state of the atmosphere very well. Greater numbers of observations will help with short-term forecasts but we cannot expect to improve on them by decreasing the grid size. New information acquired will lead to new science, which will complicate the decision making process and become a catalyst. The return value to customers is really the prognostic. Most customers do not expect anything right now and do not yet know about VII.

Appendix C

Data Elements Considered in Computational Requirements for WDT	
Year	Vehicle Velocity
Month	Heading
Day	Hours of Operation
Hours	Atmospheric Temperature
Minutes	Atmospheric Pressure
Seconds	Wiper State
Elevation	Rain Sensor
Latitude	Sun Sensor
Longitude	Headlights
Accelerometer Data (x, y, z)	ABS
Traction Control	Stability Control

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