Enhancing Road Weather Information Through Vehicle Infrastructure Integration (VII)

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ABSTRACT

Vehicle Infrastructure Integration (VII) represents a concept that has the potential to aid in the reduction of weather-related accidents on U.S. roadways, while increasing surface transportation mobility and efficiency. Technological advancements in the automotive and telecommunications industries have resulted in the ability of vehicles to acquire and utilize high temporal and spatial resolution information associated with environmental and roadway conditions. VII would enable vehicle-to-vehicle and vehicle-to-infrastructure communications through Dedicated Short Range Communications (DSRC-wireless radio communication at 5.9 GHz). This capability could potentially serve as a means of gathering and distributing vehicle data in support of applications and products designed to diagnose and predict road weather conditions. It is believed that the inclusion of VII-enabled data in road weather applications will improved weather and road condition analyses and forecasts.

This paper summarizes the vehicle data elements that likely would contribute to the development and improvement of road weather products. A synopsis of probable VII product

enhancements is provided along with examples of how vehicle data can be used in the application development process. Developing a broad understanding of how to utilize vehicle data properly will require a significant amount of research. Research needs aimed at addressing the technical issues and barriers associated with the use of VII-enabled data are discussed.

INTRODUCTION

An investigation of vehicle crashes spanning from 1995 through 2004 revealed that each year there are over 1,500,000 crashes that occur during poor weather conditions, which result 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.). Adverse weather not only affects safety, but leads to reductions in capacity, lower traffic volumes and increased delays *(2)*. Improvements in the diagnosis and prediction of hazardous weather and road conditions, along with timely dissemination of this information to stakeholders, would reduce the annual number of crashes on U.S. roadways and improve mobility and efficiency.

In an effort to mitigate the impact weather has on the national roadway system, several recent reports *(3,4,5)* 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.

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, which will foster improvements in the accuracy and timeliness of road weather information. Such improvements will also translate into new and improved decision support tools and products for end users.

The goals of this paper 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.

VEHICLE INFRASTRUCTURE INTEGRATION

This paper discusses the viability of using VII data to construct weather-related applications in support of vehicle safety and mobility. The complexities of the VII architecture and probe message processes are not discussed here in detail due to the paper length limitation, but it should be noted that the viability 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 paper for further information. It should be noted that details associated with the VII architecture and probe message processes are still evolving.

Architecture and Probe Message Processes

The VII program comprises 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 *(6)*. 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, lane departure, and collision notification warnings. Other less critical examples of applications that could be supported by the VII framework include signal timing optimization and electronic toll payments. Although these applications are less critical compared to safety applications, they would contribute to improving road mobility and efficiency.

The VII concept is based on the idea of vehicles as probes. As vehicles traverse the nation's roadways, they collect a variety of information ranging from on-board diagnostics to measurements of the environment. When a vehicle comes within range of the Road Side Equipment (RSE), selected data elements will be wirelessly transmitted to the RSE, routed to the VII network, and made available to data subscribers. Vehicles will also exchange 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 commercial applications. A critical component in the road weather application development process is understanding how vehicle data elements are produced, stored, and transmitted from the vehicle to the infrastructure.

Data elements collected by vehicles can 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.

A snapshot is a collection of vehicle data elements (e.g. outside air temperature, wiper status, headlight setting, etc.) valid at a specific time. Snapshots also contain the time the snapshot was taken and the heading, location, and speed of the vehicle. Snapshots can be generated in three ways: periodically, event triggered, or by vehicle starts and stops *(7)*. Periodic generation will occur at prescribed intervals based on the movement of a vehicle between RSEs. For example, 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 periodic snapshot interval when the vehicle speed is between 20 and 60 mph *(7)*. 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 an event-triggered snapshot. Finally, when a vehicle begins moving or comes to a stop, a snapshot will be generated. Starts and stops are based on well-defined criteria. Independent of what method results in a snapshot, all available vehicle data elements will be included in the snapshot. A maximum of 30 snapshots will be stored on a vehicle at any one time; however, this number is subject to change.

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. A summary of these mechanisms has been presented to supply the reader with fundamental background information regarding VII architecture and probe message processes, and also provide a sense of the complexities involved in vehicle data acquisition and flow based on this methodology.

WEATHER-RELATED VEHICLE DATA

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 activation, and stability control, 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 additional atmospheric and road condition parameters.

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? Table 1 provides a summary of vehicle data elements that have been identified as having potential to contribute to the enhancement of weather and road condition products. The information supplied in the table assumes that vehicle location (latitude, longitude) and time will be transmitted along with the vehicle data elements noted in the table.

TABLE 1 Weather Related Vehicle Data Elements (m = data element currently available on most production vehicles, s = data element currently available on some production vehicles, n = data element not currently available).

Road Weather Variables	Corresponding Vehicle Data Elements	Challenges and Issues	Comments
Air temperature	• Exterior temperature (m) • Hours of operation (s) • Elevation (s)	• Multiple sensors for the same parameter possible on vehicle • Sensor placement • Sensor bias • Multiple sensor manufacturers	• Data will 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 minutes after startup. The time it takes to reach equilibrium will depend on difference between the ambient temperature and initial sensor temperature.
Relative humidity	• Relative humidity (n)	• 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 (m) • Vehicle speed (m) • Heading (s) • Rate of change of steering wheel (force required to maintain current heading). (s)	• 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 (m) • Rain sensor (s) • Exterior temperature (m) • Vehicle speed (m) • Ambient noise level (s)	• Multiple sensors for the same parameter possible on one vehicle • Sensor placement • Sensor bias • Multiple sensor manufacturers • Human factor issues related to wiper usage	• 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 (s) • Headlights (m) • Adaptive Cruise Control (ACC) radar (s) • Vehicle speed (m) • Elevation (s) • Relative humidity (n)	• 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	• Exterior temperature (m) • Sun sensor (s) • Pavement temperature (n)	• Multiple sensors for the same parameter possible on one vehicle • Sensor placement • Sensor bias	• A small number of maintenance vehicles are currently outfitted with pavement temperature sensors, so these data could be used to evaluate their potential.

		• Multiple sensor manufacturers • Pavement temperature not widely available	• 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	• Exterior temperature (m) • ABS (m) • Traction control (s) • Stability control (s) • Pavement temperature (n) • Brake (m) • Accelerometer data (m)	• 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.

Although Table 1 presents a wide-ranging list of potential vehicle data elements, it is possible additional elements exist that have the ability to contribute road weather information. In any case, effective use of weather-related mobile data will potentially be based on a number of factors, some of which have been noted. Table 1 outlines several issues associated with the use of mobile data. These issues express the need to account for possible differences in the sensors 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. Knowledge regarding the way in which vehicle operators interact with and use on-board systems may also be necessary. This information could be used to refine products that are based on vehicle data. Finally, not all mobile data will be available in the quantities needed to support applications; it could be several more years before certain variables (e.g. pavement temperature) are widely accessible. These challenges and issues are discussed in further detail in the Research Needs section of this paper.

The utilization of data from mobile platforms is not new in the weather community as ship-based observations have been used for many decades. 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.

Case Examples

The efficacy of VII-enabled data is illustrated in Figures 1 and 2. Figure 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 scans) from the Detroit WSR-88D

(Weather Surveillance Radar 88 Doppler) 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. Lighter shading indicates lower reflectivity and darker shading indicates 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. Temperature 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 1A shows the vehicle driving shortly after noon (17:12Z) on 16 February. Z stands for Zulu time, which is equivalent to Coordinated Universal Time (UTC). 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 station about half an hour earlier. By 17:58Z, 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. Figures 1C and D capture the vehicle moving to the northwest along Interstate 75 at 23:25Z and 23:49Z, respectively. In Figure 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.

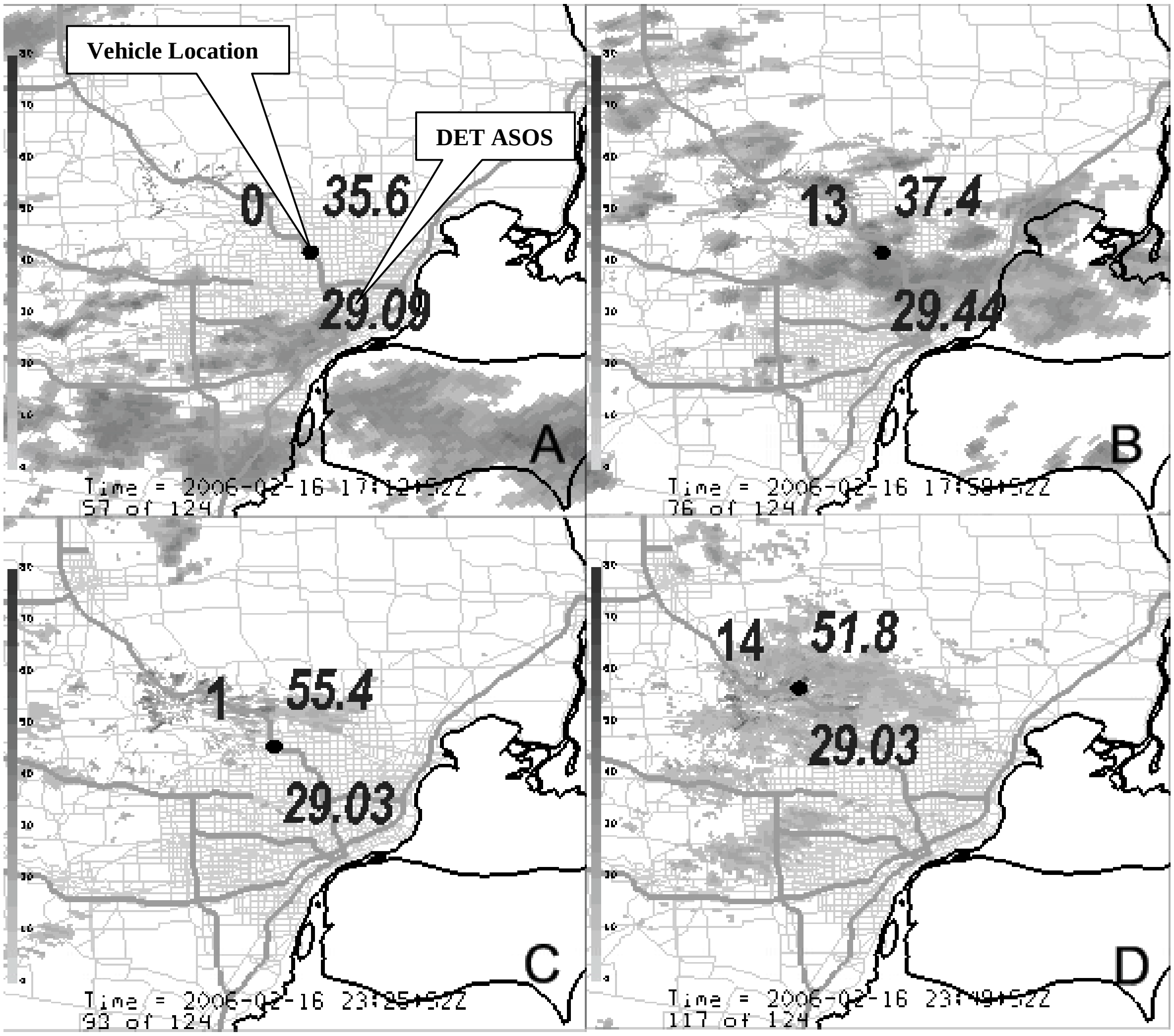

FIGURE 1 Vehicle data valid at 17:12Z (A), 17:58Z (B), 23:25Z (C), and 23:49Z (D) on 16 February 2006 overlaid with WSR-88D radar data. Vehicle data include vehicle position (black circle), wiper state (to the upper left of vehicle location), atmospheric temperature (^{o}F) (upper right), and barometric pressure (inches Hg) (lower right). Vehicle data courtesy of DaimlerChrysler. Z stands for Zulu time, which is equivalent to Coordinated Universal Time (UTC). Subtract five hours for local time.

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, 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 2. The data elements are identical to those described previously (i.e. wiper state, temperature, and pressure).

At approximately 21:56Z (Figure 2A), the DaimlerChrysler vehicle begins to head 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 black arrow. As the vehicle progresses southward, there is an increase in reported air temperature (Figure 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 2C and D). These characteristics have been observed during 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.

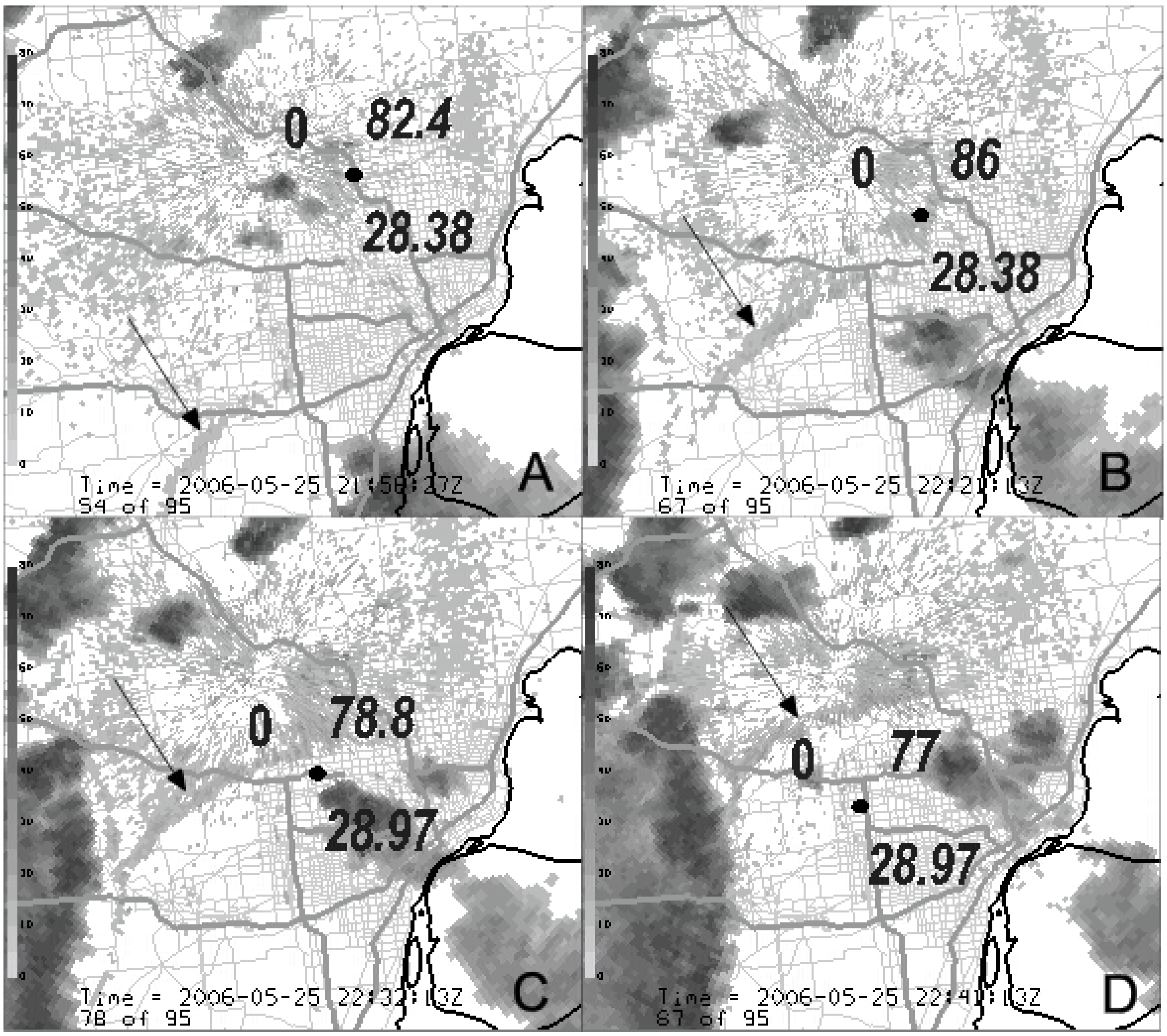

FIGURE 2 As in Figure 1, except valid times are 21:56Z (A), 22:21Z (B), 22:32Z (C), and 22:41Z (D) on 25 May 2006. Arrow denotes the location of outflow boundary.

Both of these cases demonstrate the potential benefit of vehicle data in the diagnosis of atmospheric conditions. It is also readily apparent that the proliferation of VII-enabled data could result in information on spatial and temporal scales that may 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.). Such information can be used to initialize numerical models, which presently have difficulty forecasting smaller scale structures such as these.

WEATHER & ROAD CONDITION PRODUCT IMPROVEMENTS ENABLED BY VII

In this section, weather and road condition product concepts enabled or improved by vehicle data are presented. 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. Examples presented herein were selected because it was felt that they were particularly relevant to the surface transportation community. Some of the surface transportation stakeholder categories that are likely to benefit from weather and road condition products enhanced with vehicle data include traffic management, incident management, maintenance (winter and non-winter), travelers, emergency management, automobile manufacturers, and vehicle operators.

A variety of weather and road condition products will likely be improved with vehicle data. Moreover, the availability of vehicle data will open the door to new road weather innovations. In terms of weather, the primary potential contribution of vehicle data will be its ability to help characterize the lowest levels of the atmospheric boundary layer. Improvements linked to VII data are also expected to include advancements in the diagnoses of current weather and road conditions and improved weather and road condition forecast capability.

Weather and road condition improvements that are likely to be enabled with vehicle data include, but are not limited to:

- Improved identification of precipitation type
- Reducing radar anomalous propagation (AP)
- Improved identification of virga (precipitation not reaching the ground)
- Improved identification of foggy regions
- Improved initialization of surface conditions for weather models
- Improved weather analysis and prediction in complex terrain
- Improved identification of slippery pavement
- Improved knowledge of pavement temperatures
- Improved knowledge of pavement condition (dry, wet, snow covered, etc.)

Although each of these topics could be discussed at length, only a few are highlighted below in an attempt to underscore the likely benefits of VII-related data elements.

Reducing Radar Anomalous Propagation (AP) and Virga

Doppler weather radar data are used widely for many weather applications and products throughout the country. The National Weather Service (NWS) and Department of Defense 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.

On many occasions, radar will indicate that light precipitation is occurring when in fact there is no precipitation in the area. Such false returns can be 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 valid or an artifact. DOT maintenance personnel, who routinely use radar data to guide tactical decision making, take appropriately conservative measures to begin maintenance operations when precipitation is anticipated. If the radar information turns out to be an artifact, the resources used to begin operations were wasted. Anomalous propagation is not rare and often occurs after precipitation, on clear nights, and after the passage of shallow cold fronts.

Unlike AP, virga occurs when the radar properly indicates widespread precipitation even though no precipitation is reaching the ground. When the lower atmosphere is dry, the likelihood of virga increases. This situation can last for hours and it is difficult for users to determine if and when the precipitation will reach the ground. Transportation maintenance (winter and non-winter) and traffic management personnel require accurate radar products to plan operations. Travelers also need accurate surface precipitation information.

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

Data from vehicles could be used to help determine if precipitation is occurring in the area in question. The density of vehicle observations will likely 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.

Improved Initialization 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, 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 datasets 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.

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 have the potential to 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.

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. 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 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 capability to process the data. If a weather model was configured to have 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 add value, as they would help define the state of the atmosphere on a scale closer to that of the model.

IN-VEHICLE INFORMATION SYSTEM PRODUCTS ENABLED BY VII

Vehicle Infrastructure Integration technology will not only enable vehicles to communicate probe data to external systems, but 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 internet, and until cell phone technology became dominant, phone service was unavailable. Wireless communication technologies are becoming more reliable, more widespread, and less expensive, 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. It 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 would 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 were 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 beneficiary of the data collected. 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). In-vehicle weather and road condition products that are likely to be of most interest to drivers include:

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

The following route specific weather advisories should also be provided to drivers:

- Tornado warning
- Severe thunderstorm warning
- High wind warning
- Flash flood warning
- Blizzard warning
- Hurricane warning

RESEARCH NEEDS

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. 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-related products.

Probe Message Processes

As previously noted, VII probe message processes will be critical in 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 likely be associated with periodic snapshots. These types of 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 may be deleted in favor of other snapshots. Under some circumstances (e.g. heavy traffic), this characteristic may 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.

Adoption Rates

Another factor of VII that will determine how, when, and where applications can be developed and implemented is related to the deployment rate of VII technologies. 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.

Data Processing

A potential key advantage of VII is the amount of data that will be made available for the application development process. 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 could potentially flow through the VII network, but it could 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 may facilitate the use of large amounts of vehicle information in some algorithms and applications.

Data Quality and Accuracy

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 impacted 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.

Quality Control

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 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 quality control procedures on VII data will be necessary to ensure the highest quality data possible. Research is needed to explore the types of quality control 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.

Data Fusion

In order to create weather-related applications utilizing VII-enabled data, it will be necessary to combine vehicle data with other complementary datasets 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 could greatly aid in identifying and defining small-scale weather features and localized road conditions; however, new data fusion techniques would need to be developed to take full advantage of VII data. 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. In addition, the utility and value of ingesting mobile data into other weather products should also be examined.

Numerical Model Forecasts

The availability of VII-enabled data may facilitate substantial improvements in the ability of numerical models to forecast changes in the atmosphere accurately, 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 use 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 numerical model forecasts of the boundary layer, including data assimilation of mobile data, quality and quantity requirements, and the utilization of indirect atmospheric measurements.

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 could be incorporated directly into algorithms and applications, and result in more accurate analyses and forecasts of road weather parameters.

SUMMARY AND CONCLUSIONS

The potential use of VII-enabled data in weather-related applications and products for surface transportation is being examined. The availability of VII-enabled data would almost certainly lead to improvements in road weather products. Advancements in the diagnosis and prediction of adverse weather and road conditions could be immediately 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.

Case studies in which vehicle data were compared with conventional weather data were presented herein. These cases revealed the potential value of mobile data as a good correlation between vehicle data elements (wiper state, temperature, and pressure), radar data, and surrounding surface observations existed. Vehicle data acquisition and distribution enabled by VII will likely 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 this discussion is that a significant amount of research will be required to understand the feasibility of using 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 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, it is anticipated that vehicle data will contribute in a positive manner to the generation of improved weather and road condition products because of the large volume of data, distribution of observations, and frequent updates.

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