JOINT TRANSPORTATION RESEARCH PROGRAM

INDIANA DEPARTMENT OF TRANSPORTATION
AND PURDUE UNIVERSITY

Extraction of Vehicle CAN Bus Data for Roadway Condition Monitoring

**Howell Li, Enrique Saldivar-Carranza,
Jijo K. Mathew, Woosung Kim, Jairaj Desai,
Timothy Wells, Darcy M. Bullock**

AUTHORS

Howell Li
JTRP Senior Software Engineer
Lyles School of Civil Engineering
Purdue University
(765) 494-9601
howell-li@purdue.edu
Corresponding Author

Enrique Saldivar-Carranza, Graduate Research Assistant
Jijo K. Mathew, PhD, Transportation Research Engineer
Woosung Kim, Software Engineer
Jairaj Desai, Graduate Research Assistant
Lyles School of Civil Engineering
Purdue University

Timothy Wells, Highway Engineer Supervisor 4
Indiana Department of Transportation

Darcy M. Bullock, PhD, PE
Lyles Family Professor of Civil Engineering
Lyles School of Civil Engineering
Purdue University
Principal Investigator

JOINT TRANSPORTATION RESEARCH PROGRAM

The Joint Transportation Research Program serves as a vehicle for INDOT collaboration with higher education institutions and industry in Indiana to facilitate innovation that results in continuous improvement in the planning, design, construction, operation, management and economic efficiency of the Indiana transportation infrastructure. https://engineering.purdue.edu/JTRP/index_html

Published reports of the Joint Transportation Research Program are available at http://docs.lib.purdue.edu/jtrp/.

TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No. FHWA/IN/JTRP-2020/20	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Extraction of Vehicle CAN Bus Data for Roadway Condition Monitoring		**5. Report Date** August 2020
		6. Performing Organization Code
7. Author(s) Howell Li, Enrique Saldivar-Carranza, Jijo K. Mathew, Woosung Kim, Jairaj Desai, Timothy Wells, and Darcy M. Bullock		**8. Performing Organization Report No.** FHWA/IN/JTRP-2020/20
9. Performing Organization Name and Address Joint Transportation Research Program (SPR) Hall for Discovery and Learning Research (DLR), Suite 204 207 S. Martin Jischke Drive West Lafayette, IN 47907		**10. Work Unit No.**
		11. Contract or Grant No. SPR-4323
12. Sponsoring Agency Name and Address Indiana Department of Transportation State Office Building 100 North Senate Avenue Indianapolis, IN 46204		**13. Type of Report and Period Covered** Final Report
		14. Sponsoring Agency Code

15. Supplementary Notes
Conducted in cooperation with the U.S. Department of Transportation, Federal Highway Administration.

16. Abstract
Obtaining timely information across the state roadway network is important for monitoring the condition of the roads and operating characteristics of traffic. One of the most significant challenges in winter roadway maintenance is identifying emerging or deteriorating conditions before significant crashes occur. For instance, almost all modern vehicles have accelerometers, anti-lock brake (ABS) and traction control systems. This data can be read from the Controller Area Network (CAN) of the vehicle, and combined with GPS coordinates and cellular connectivity, can provide valuable on-the-ground sampling of vehicle dynamics at the onset of a storm. We are rapidly entering an era where this vehicle data can provide an agency with opportunities to more effectively manage their systems than traditional procedures that rely on fixed infrastructure sensors and telephone reports. This data could also reduce the density of roadway weather information systems (RWIS), similar to how probe vehicle data has reduced the need for micro loop or side fire sensors for collecting traffic speeds.

17. Key Words controller area network, CAN bus, on board diagnostics, enhanced probe data, winter roadway condition monitoring, inclement weather conditions, wheel slip, traction control, anti-lock brake (ABS) systems	**18. Distribution Statement** No restrictions. This document is available through the National Technical Information Service, Springfield, VA 22161.		
19. Security Classif. (of this report) Unclassified	**20. Security Classif. (of this page)** Unclassified	**21. No. of Pages** 44 including appendices	**22. Price**

Form DOT F 1700.7 (8-72)   Reproduction of completed page authorized

EXECUTIVE SUMMARY

Introduction

Obtaining timely information across the state roadway network is important for monitoring the condition of the roads and the operating characteristics of traffic. One of the most significant challenges in winter roadway maintenance is identifying emerging or deteriorating conditions before significant crashes occur. For instance, almost all modern vehicles have accelerometers, anti-lock brake (ABS), and traction control systems. This data can be read from the Controller Area Network (CAN) of the vehicle and, combined with GPS coordinates and cellular connectivity, can provide valuable on-the-ground sampling of vehicle dynamics at the onset of a storm. We are rapidly entering an era where this vehicle data can provide an agency with opportunities to more effectively manage their systems than traditional procedures that rely on fixed infrastructure sensors and telephone reports. This data could also reduce the density of roadway weather information systems (RWIS), similar to how probe vehicle data has reduced the need for micro loop or side fire sensors for collecting traffic speeds.

Methods

Over the course of the project, the research team engaged a number of industry partners to collaborate, consult experts, test equipment, and share findings of the research with stakeholders. Vehicles from three different manufacturers were used for testing CAN data elements in nine categories. A system for receiving, transmitting, and processing the CAN data was piloted using a vehicle interface (VI) with an embedded computer, cellular networks, and back-office data system at Purdue University. A series of dashboards for transforming and displaying the data were developed as part of the user interface deliverables.

Findings

The findings of this research were as follows:

1. The team successfully piloted an integrated CAN Bus road monitoring system to identify roadway hazards in real-time during winter events. This enables data-driven decision-making for practitioners.
2. The team successfully identified, tested, and integrated CAN Bus data elements from nine categories (speed, GPS, braking systems, drivetrain, accelerometer, steering, climate, lighting, and emergency systems) into existing dashboard interfaces for identifying winter road and hazardous conditions.
3. The team found braking and wheel counter data to be the most useful for early indication of winter conditions.
4. The volume and velocity of the CAN Bus data will be the most challenging to implement over a large fleet as many signals are generated at millisecond fidelity. To help with the scaling process, only relevant signals from the vehicle should be transmitted to the agency using efficient protocols to a scaled-out, high-performance back-office system, or cloud data center.
5. A few emerging off-the-shelf products from automotive manufacturers and equipment suppliers are starting to provide roadway metrics from CAN Bus data. Continued engagement and collaboration with these industry partners will enable INDOT to make use of and transition to scalable, commercially-supported, state-of-the-art platforms.

Implementation

Near- and medium-term recommendations are as follows, with action items for each term:

1. Near-term (6–18 months)

   a. Develop relationships with CV data providers to integrate hard braking events into Traffic Management Center (TMC) operations.
   b. Develop relationships with CV data providers to integrate loss of friction data (ABS or traction control) into TMC operations and coordinate with winter weather maintenance colleagues.
   c. Develop relationships with CV data providers to identify locations of pavement distress or work zone irregularities using vehicle pitch, roll, and steering.

2. Medium-term (18 months or longer)

   a. Evaluate the feasibility of capturing weather-related data such as windshield wipers, defroster settings, and temperature readings to enhance TMC and winter weather management activities.
   b. Develop plans to integrate this data into business processes used by central office, districts, sub-districts, and units. The winter weather data is particularly valuable to sub-districts and units.

CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ACRONYMS

ABS	Anti-Lock Braking System
ADAS	Advanced Driver Assistance Systems
AVL	Automatic Vehicle Location
CAN	Controller Area Network
DBC	Database CAN
DTC	Diagnostic Trouble Codes
FHWA	Federal Highway Administration
FTP	File Transfer Protocol
GPS	Global Positioning System
GRIB	GRidded Information in Binary
HRRR	High-Resolution Rapid Refresh
HTTP	Hyper Text Transport Protocol
IQR	Inter-Quartile Range
JSON	JavaScript Object Notation
MARWIS	Mobile Road Weather Information Sensor
MQTT	Message Queuing Telemetry Transport
MRMS	Multi-Radar/Multi-Sensor
NASA	National Aeronautics and Space Administration
NLDAS	North American Land Data Assimilation System
NOAA	National Oceanic and Atmospheric Administration
NSSL	National Severe Storms Laboratory
OBD	On-Board Diagnostics
SQL	Structured Query Language
TPMS	Tire Pressure Monitoring System
USB	Universal Serial Bus
USDOT	United States Department of Transportation
VI	Vehicle Interface
Wi-Fi	Wireless Fidelity

1. PROJECT OVERVIEW

1.1 Introduction

Over the course of the project, the research team engaged a number of industry partners to collaborate, consult experts, test equipment, and share findings of the research with stakeholders. Vehicles from three different manufacturers were used for testing CAN data elements in nine categories. A system for receiving, transmitting, and processing the CAN data was piloted using a vehicle interface (VI) with an embedded computer, cellular networks, and back-office data system at Purdue University. A series of dashboards for transforming and displaying the data were developed as part of the user interface deliverables.

As an example, Figure 1.1 illustrates how speed and hard braking CAN data can enhance roadway monitoring. Vehicle data is used to populate the charts, colorized by the speed of vehicles. In this example, a 6-mile queue developed in a 3-hour period following a crash. This queue can be seen using aggregated segment-level speed data in Figure 1.1a. Callout i shows the location of the crash at the beginning of the queue where the initial drop in aggregated speed is detected. Figure 1.1b shows the event in more detail using vehicle trajectories. Vehicles between 17:00 and 17:30 were at a standstill with one of the vehicles keying off (callout ii). CAN Bus data goes one step further by using accelerometer data from vehicles to track the locations of hard braking, color-coded by how quickly a vehicle was travelling when the brakes were applied, in Figure 1.1c. Callout iii shows an initial pair of hard braking events detected about 15-minutes earlier than the earliest speed drop. Hard braking events persisted an hour into the event (callout iv), extending up to six miles from the crash.

Although only hard braking is now commercially available from Connected Vehicles (CV), this report illustrates how data from traction control and ABS systems could be used in a similar manner to identify onset of winter weather using both a connected Audi and mobile roadway weather monitoring equipment mounted on INDOT trucks.

Figure 1.2 illustrates a "heatmap" much like Figure 1.1a during a winter storm on I-465, overlaid with trajectories of snow plows instrumented with a MARWIS sensor that reports friction values. The tracks show good pavement conditions before the storm (callout i), slippery conditions during two phases of the storm (callout ii and iii), and recovery (callout iv). We anticipate that, much like the hard-braking data that is now commercially available, similar winter operations data will soon be available in real-time.

From the results of the study, the below points provide an overview of the implementation opportunities for CAN Bus technology.

1. Near-term (6–18 months):

   a. *Hard-braking data.* Develop relationships with CV data providers to integrate hard-braking events into TMC operations to identify safety hazards.
   b. *Loss of friction data.* Develop relationships with CV data providers to integrate loss of friction data (ABS or traction control) into TMC operations and coordinate with winter weather maintenance colleagues.
   c. *Pavement irregularities data.* Develop relationships with CV data providers to identify locations of pavement distress or work zone irregularities using vehicle accelerometers, pitch, roll, and steering.

2. Medium-term (18 months or longer):

   a. *Weather data.* Evaluate the feasibility of capturing weather-related data such as windshield wipers, defroster settings, and temperature readings to enhance TMC and winter weather management activities.
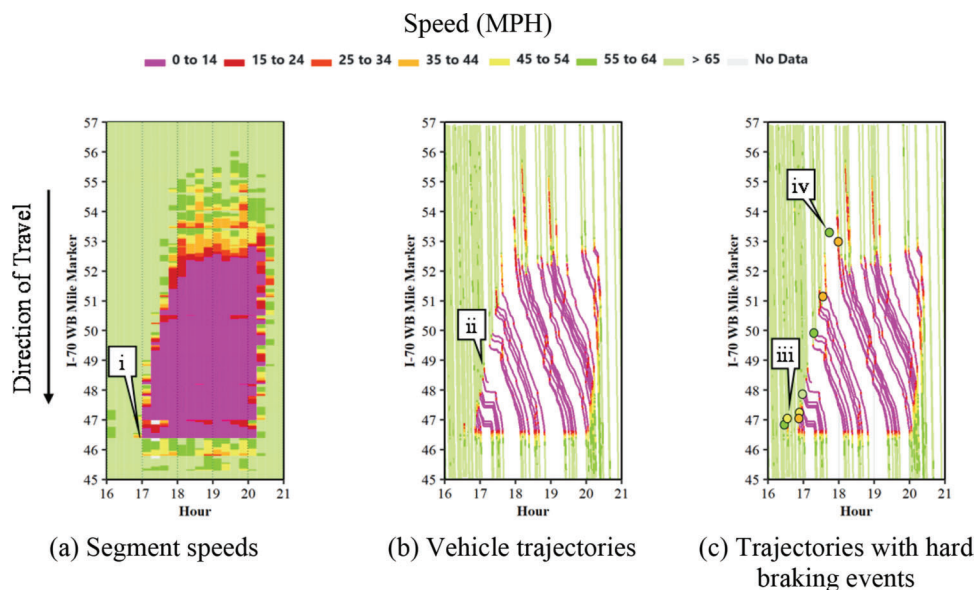
Figure 1.1   Evolution of probe and connected vehicle data.
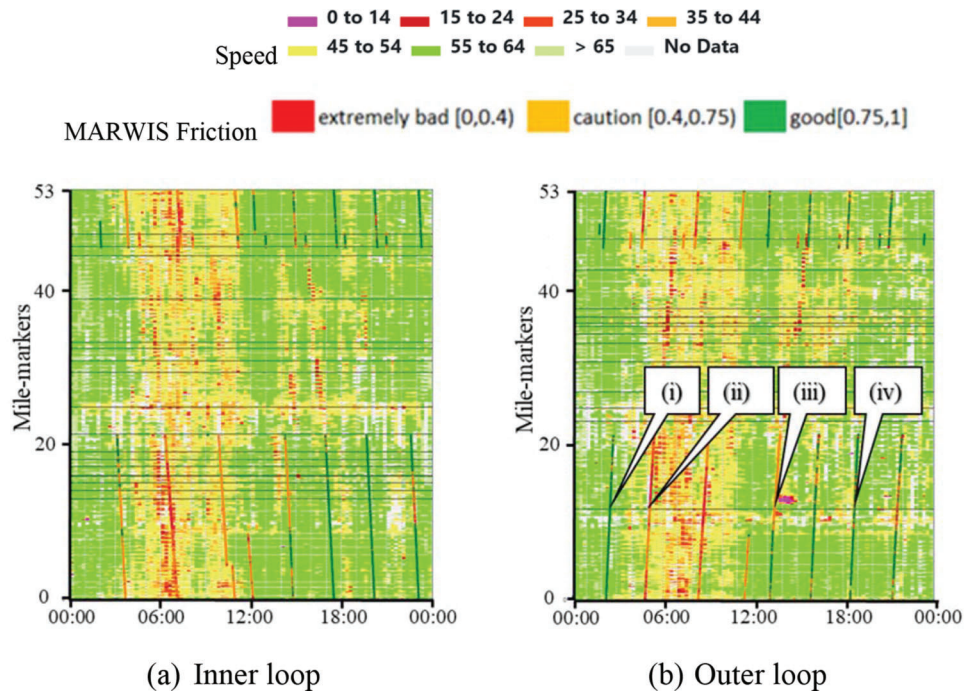
Figure 1.2 Heatmap of traffic speeds with friction overlaid on I-465, January 12, 2019.

b. *Institutionalizing business processes.* Develop plans to integrate this data into business processes used by central office, districts, sub-districts, and units. The winter weather data is particularly valuable to sub-districts and units.

1.2 Dissemination of Research Results

The following is a list of papers prepared in part during the course of this project:

- Desai, J., Mathew, J. K., Kim, W., Liu, M., Li, H., Brooks, J. D., & Bullock, D. M. (2020, January). *Dashboards for real-time monitoring of winter operations activities and after-action assessment* [Paper presentation]. Transportation Research Board 99th Annual Meeting, Washington D.C. https://doi.org/10.5703/1288284317252
- Downing, W. L., Li, H., Morgan, B., McKee, C., & Bullock, D. M. (2018, January) *Using probe data analytics for assessing freeway speed reductions during rain events* [Paper presentation]. Transportation Research Board 98th Annual Meeting, Washington D.C.
- Downing, W. L., Li, H., Desai, J., Liu, M., Bullock, D. M., & Baldwin, M. E. (January 13, 2020). *Evaluation of the high-resolution rapid refresh model for forecasting roadway surface temperatures* [Paper presentation]. 100th American Meteorological Society Annual Meeting, Boston, MA. https://ams.confex.com/ams/2020Annual/webprogram/Paper366492.html
- Li, H., Wolf, J. C., Mathew, J. K., Navali, N., Zehr, S. D., Hardin, B. L., & Bullock, D. M. (2020, March). Leveraging connected vehicles to provide enhanced roadway condition information. *Journal of Transportation Engineering, Part A: Systems*, *146*(8). https://doi.org/10.1061/JTEPBS.0000370
- Desai, J., Li, H., Mathew, J. K., Cheng, Y., Habib, A., & Bullock, D. M. (2020, November). Correlating

hard-braking activity with crash occurrences on interstate construction projects in Indiana. *Journal of Big Data Analytics in Transportation*. https://doi.org/10.1007/s42421-020-00024-x

These technical papers were prepared throughout the project and distributed to key INDOT stakeholders to facilitate early implementation of the research findings. The following sections of the technical report summarize key findings from these papers.

2. CAN BUS DATA ELEMENTS

CAN Bus data are generated by various components and devices on modern vehicles and transmitted via multiple onboard networks (Hristu-Varsakelis & Levine, 2005). General diagnostic codes and other data can be accessed by connecting to the OBD-II port. This port is typically used for routine maintenance and troubleshooting, but other data may be accessed with this interface (Hristu-Varsakelis & Levine, 2005). Depending on the vehicle, additional data can be accessed via other network interfaces besides the CAN Bus.

The data elements that are pertinent to winter roadway condition monitoring are identified and described in the following subsections. Table 2.1 provides an overview of each CAN Bus data element on the recommended implementation timeline.

2.1 Speed

Slow speeds of various vehicles at specific road segments are a good indication of heavy traffic, accidents and weather events. Cross-referencing different CAN Bus data elements narrows down what specific scenario

TABLE 2.1
CAN Bus data element implementation timeline

	Implementation Timeline		
Data Element	6–12 months	12–18 months	>18 months
Speed	X		
GPS[1]	X		
ABS	X		
Brake Pressure	X		
Traction Control Systems	X		
Wheel Counters		X	
Drive Mode		X	
Wheel Torque		X	
Longitudinal and Latitudinal Acceleration		X	
Yaw Angle		X	
Pitch and Roll		X	
Steering Angle		X	
Windshield Wipers			X
Defroster			X
Ambient Temperature			X
Lighting			X
Hazard Lights			X
ADAS and Emergency Systems			X
TPMS			X

[1]Factory equipment or after-market devices.

is happening on the road. Slow speeds detected while windshield wipers are active, preceded by a drop in the ambient temperature, would help agencies identify segments that are being significantly affected by precipitation. Further, slow speeds in combination with hazard lights being turned on could imply that there was an accident.

In general, speed data can be utilized with other CAN Bus data elements to define events. For example, a big change in vertical acceleration while traveling at a high speed may be an indication of a pothole.

2.2 GPS

GPS data has a broad variety of uses:

- GPS information helps categorize the different types of events. For example, a hard-braking event near an intersection may suggest the incursion of a vehicle in the dilemma zone, whereas a hard-braking event in a rural road could indicate animal crossings. Being able to reference vehicle events on a map enables agencies and transportation professionals to assign greater relevance to certain events of the same type according to their location.
- GPS data provides the ability to geographically locate poor road conditions, such as potholes and transverse cracks, that require of maintenance.
- Vehicle trajectories can be obtained, which provide valuable information to assess roads, such as: travel time, travel speed, volumes, capacities, delays, etc.
- GPS data can also provide useful information to evaluate signalized intersections. For example, Figure 2.1 shows 7,292 different vehicles that crossed US 231 and SR 25 in July 2019. Even though this number does not represent all the vehicles that crossed the intersection, it provides a
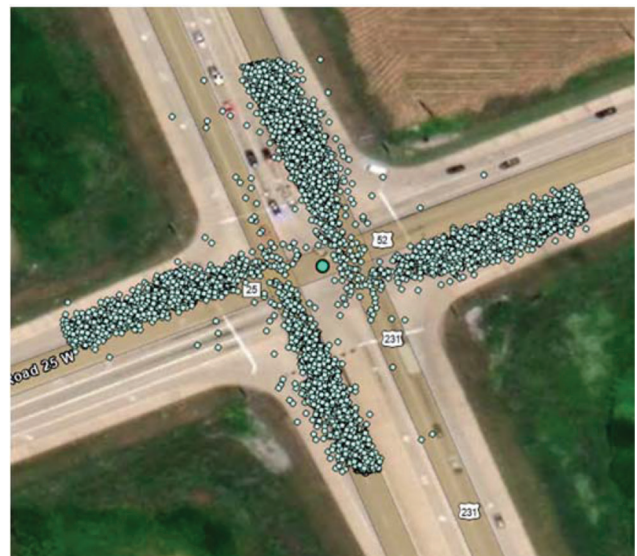
Figure 2.1 Example of crowdsourced GPS coordinates exiting an intersection over 1 month at US 231 and SR 25 in Lafayette, IN.

good comparison point if the same analysis was to be done at other intersections.

2.3 Braking Systems

2.3.1 Anti-Lock Brake Systems (ABS)

ABS intervenes in vehicle braking to prevent the wheels from locking up. The intervention occurs at

areas where there is low friction due to icy, snowy, slushy, or gravel conditions, and the brakes are applied. Typically, this occurs at intersections, in advance of a stopped queue on limited-access roadways, or at other locations where there is a need to decelerate. An example of a location where ABS intervened is shown in Figure 2.2 with an ice patch (callout i) in advance of a stop sign. This event does not get triggered during acceleration or at cruising speeds.

2.3.2 Brake Pressure

The intensity of brake pressure is a good indicator of abrupt safety hazards faced by motorists along a roadway. For instance, hard-braking events will aid agencies and transportation professionals in identifying areas with poor geometric conditions and studying dilemma zone exposures at intersections. Figure 2.3 shows an example of the brake pedal intensity data collected during the study.

Figure 2.2 Icy area in advance of a stop sign that triggers ABS intervention.

In addition, during inclement weather conditions changes in typical brake pressure from normal can be used as an indicator for deteriorating conditions. Figure 2.4 shows the results of an experiment conducted over the course of a winter storm at the approach of a signalized intersection. Eighteen runs were made throughout the storm starting from dry conditions. Figure 2.4a shows the brake pressure during each approach and callout i shows the period where falling snow was visible or had accumulated on the road. As the chart shows, before snow started (Figure 2.4b) there was comparatively less braking pressure applied than during the period when snow was visible to the driver (Figure 2.4c). Detailed data and analysis can be found in Appendix A.

2.4 Drivetrain

2.4.1 Traction Control Systems

Traction control systems are designed to maintain vehicle stability by using electronic means to modulate the brake force, throttle, and/or engine output when loss of friction is detected on one or more wheels of the vehicle (Moran & Grimm, 1971). For example, in slippery conditions when the throttle is applied, the engine output may be greater than the amount that can be put down by any one of the tires. During a winter event, having the ability to detect locations of traction control intervention events provides a considerable advantage in making real-time maintenance decisions.

2.4.2 Wheel Counters (Ticks)

Wheel counters are electrical pulses that are generated products of a wheel's rotation. These pulses can be utilized to calculate the wheel's position, speed and

Figure 2.3 Brake pedal intensity.
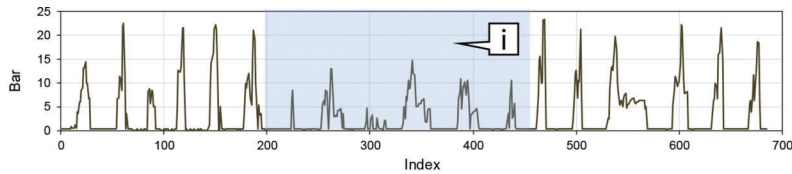
(a) Braking pressure

(b) Before snowfall

(c) During snowfall

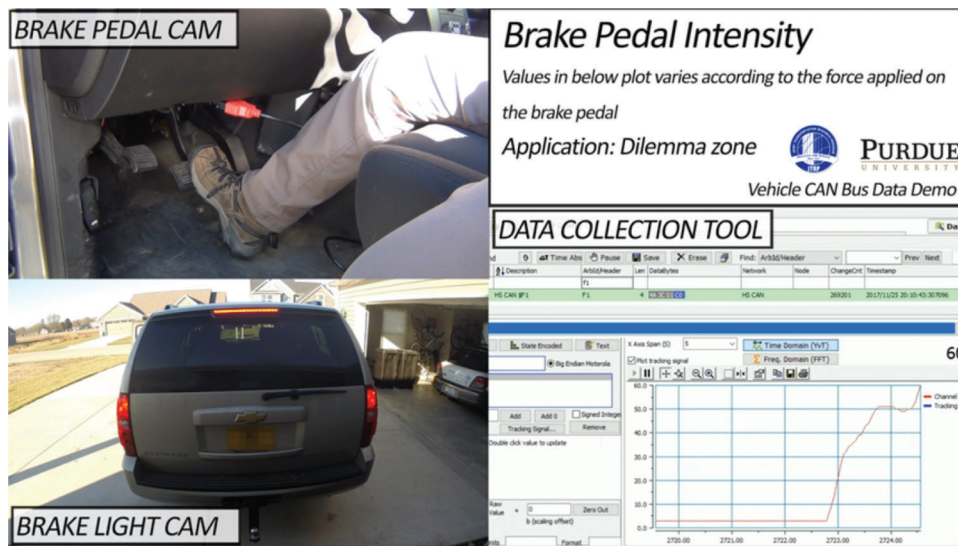**Figure 2.4** Changes in brake pressure intensity during snowfall event.
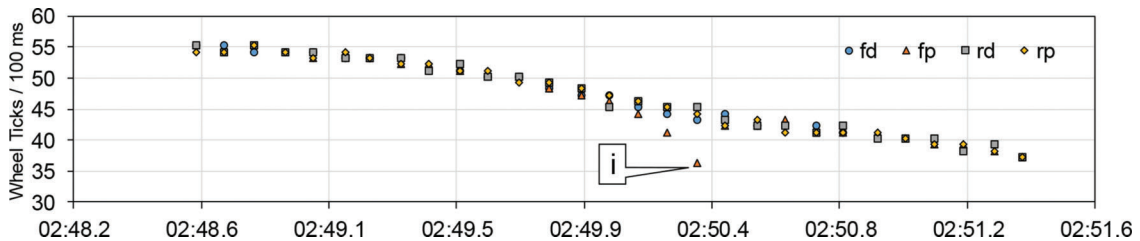
Figure 2.5 Measured wheel counter (ticks) during a slippery condition.

acceleration. This data can provide valuable information on various scenarios, such as the following:

1. Identification of road surface: gravel, asphalt or concrete. Small changes of wheel speed occur constantly when a vehicle is traveling on gravel. In contrast, when a vehicle is on asphalt or concrete the speed is almost constant.
2. The identification of sudden changes on wheel acceleration for short periods of time are a good indication of a vehicle going over a pothole.
3. A significant difference in the speed of wheels that are on the same axis during winter season can be a useful warning to agencies of road segments with icy conditions.

Wheel slippage can be detected using high-speed wheel counter data such as in Figure 2.5. The graph plots the speed of each wheel at 100 ms during a braking event (fd: front driver; fp: front passenger; rd: rear driver; rp: rear passenger). At minute 02:50.3, the vehicle's front passenger wheel locks up over a slick area (callout i) where the wheel slowed down considerably compared to the three other wheels.

2.4.3 Two-Wheel Drive, Four-Wheel Drive, and All-Wheel Drive

A vehicle may operate in different modes depending on the drivetrain that sends power to any number of wheels on the vehicle. In low-friction scenarios, the wheels may slip differently for an axle that is part of the drivetrain compared to a dead axle. For two-wheel drive vehicles, it is important to know whether the vehicle is front or rear-wheel drive so that the correct CAN messages are interpreted accordingly. For four-wheel drive applications, this is typically configurable by the driver for rear-axle drive only, or power to both front and rear axles. Some vehicles can also engage locking differential to output torque evenly across each side of an axle, typically used for low-speed, rough road conditions. All-wheel drive vehicles use either torque biasing, or sensors and electronics to distribute torque on any axle and wheel automatically without explicit driver input (Armantrout & Dick, 1971; Torii et al., 1986; Zomotor et al., 1986).

2.4.4 Wheel Torque Distribution

For vehicles that have electronically-controlled drivetrains, depending on the road conditions and driver input, the torque output to each wheel is adjusted automatically to maintain vehicle stability and control. These adjustments in wheel torque distribution can be monitored in the CAN data to determine when the vehicle drives through inclement conditions, such as driving over a patch of snow that is not evenly distributed across four wheels. These features are applicable for both two-wheel drive and four/all-wheel drive vehicles depending on vehicle equipment (Torii et al., 1986; Zomotor et al., 1986).

2.5 Accelerometer

2.5.1 Longitudinal, Latitudinal, and Vertical Acceleration

In addition to the vehicle dynamics, the acceleration data has the potential to identify roadway characteristics and pavement quality. Several studies have established this in the literature using inferior smartphone data (Alessandroni et al., 2014; Buttlar & Islam, 2014; Hanson et al., 2014; Islam et al., 2014). One of the early applications of this data involves the detection of potholes. Figure 2.6 illustrates the team collecting the lateral acceleration data from the vehicle. This type of data can be integrated with a web dashboard to show on a map where and when the harsh accelerations were experienced (Figure 2.7).

In the absence of detailed brake pedal pressure or activation data, longitudinal acceleration can serve as a proxy for hard braking events. When the brakes are applied forcefully, causing the vehicle to decelerate rapidly, the accelerometer registers a high value along the longitudinal axis. Figure 2.8 plots the hard-braking events per mile for 25 construction zones in both directions throughout the state (blue bars) and compares this number with crashes in the same zone (orange line). A strong relationship is evident since the number of hard braking increases as the number of crashes also increases.

2.5.2 Yaw Angle

The magnitude of the yaw angle can provide valuable information on the change in direction of the vehicle. Yaw angles too big while vehicles travel at high speeds might indicate loss of stability and friction, unexpected sharp turns, or other arising safety concerns.

2.5.3 Pitch and Roll

Pitch and row position, speed and acceleration can provide good road-condition assessments. Sudden changes of acceleration for brief periods of time can help with the detection of potholes. Moreover, quick
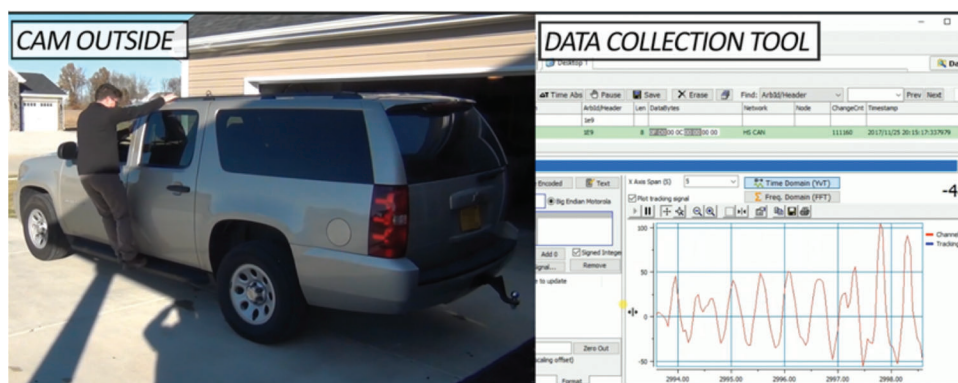

Figure 2.6 Lateral acceleration.

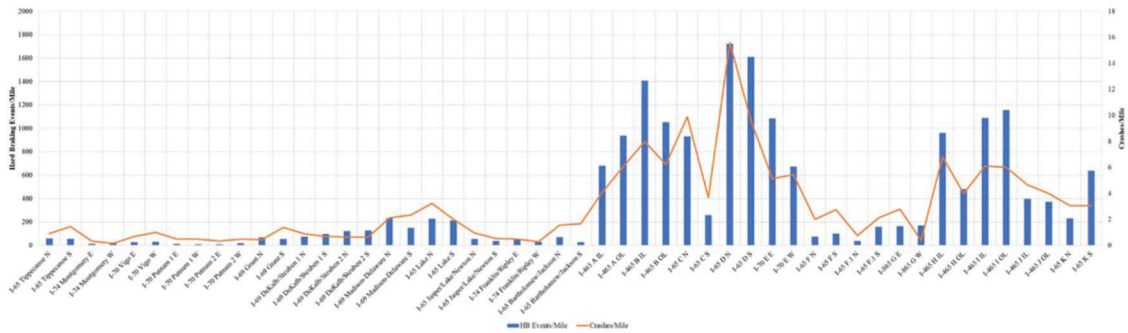**Figure 2.7** Dashboard for pothole detection using lateral acceleration.

Figure 2.8 Plot of hard crashes/mile vs. hard braking events/mile for July and August 2019 construction zones.

Figure 2.9 Dashboard view of pitch and roll angle on a Ford F-150.

changes on roll speed might indicate a shoulder that may be challenging to negotiate for drivers. Figure 2.9 shows an example of a dashboard interface for pitch, roll, and steering angle in a late-model Ford F-150.

This information, in combination with GPS data, indicates what type of roadway maintenance is required and where it is needed. Even though these indicators may not be accurate enough to replace standard road-quality measurements, they can provide agencies and contractors guidance on which roads are worth looking at with more detail.

2.6 Steering Angle

Steering angle indicates the driver's steering input to the vehicle. In inclement road conditions, it can reveal the steering response of a driver relative to how a vehicle is actually moving or turning by comparing with data from other sensors such as yaw. Figure 2.10a shows testing of the steering angle with CAN Bus analysis software. As the driver turns the wheel to the right (callout i), the steering angle value increases positively on the computer's interface (callout ii). Figure 2.10b shows the real-time data plotted as the steering wheel is turned.

2.7 Climate and Temperature

2.7.1 Windshield Wipers

Windshield wipers are usually activated during weather related events. This data will be a great source of information to do the following:

1. Detect weather events such as rain, snow, and icy conditions.
2. Compare and contrast actual ground conditions with weather forecast models.

Figure 2.11 shows an example collecting the CAN Bus data coming from the activations of the windshield wiper.

2.7.2 Defroster

Defroster activation can indicate whether a vehicle is experiencing in-cabin visibility issues due to high humidity, windshield icing or frost conditions (Figure 2.12). Segments of roadway that experience high levels of defroster activation may be a concern for increased driver workload and on-road attentiveness. The data is low-frequency as only the change in defroster mode (on or off) is required to be saved.

2.7.3 Ambient Temperature

Ambient temperature, usually received by sensors located in the bumper of a vehicle, can detect changes in air temperature above the roadway as a proxy to where ice may be forming. In the past decade, a number of initiatives across the country have begun to crowdsource weather reports using mobile applications (Elmore et al., 2014; FHWA, 2017). The reports allow agencies to rapidly assess on-the-ground weather conditions over a large area where road weather sensing infrastructure may not be available. Ambient temperature decoded from CAN data that is integrated with the cloud can allow agencies to automatically monitor temperatures without user input and reduce driver distraction with a method that is also scalable.
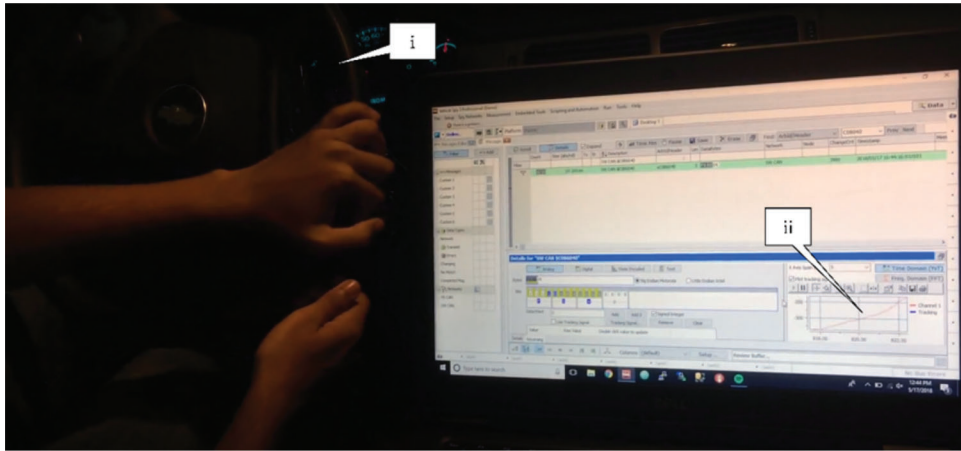
(a) Turning of steering wheel and sampling data output on laptop
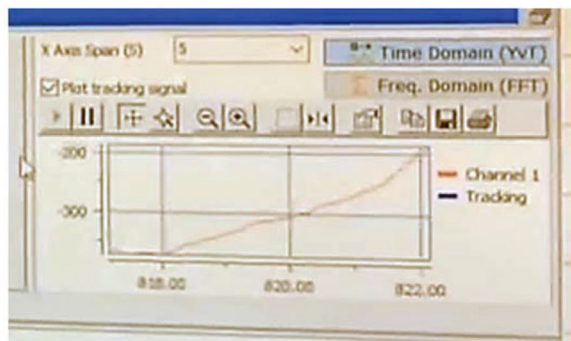
(b) Plot of steering angle data from callout ii

Figure 2.10 Steering angle testing on 2014 Suburban.
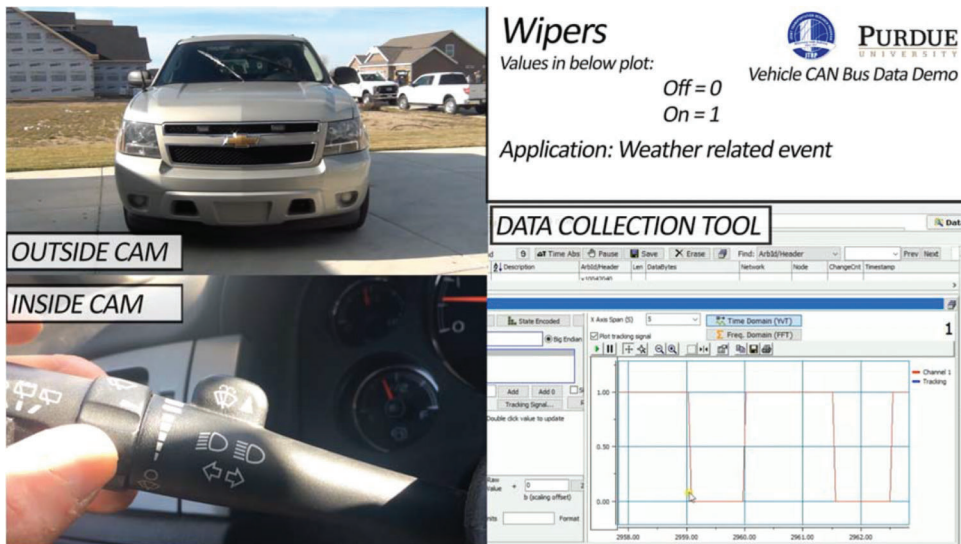
Figure 2.11 Windshield wipers.

2.8 Lighting Systems

The lighting system is one of the most basic features on a vehicle that affects driver visibility. Common in most vehicles produced today, light sensors detect and automatically adjust, and turn on and off headlights (Groh, 1997). Some of the more sophisticated ADAS systems also control high beam actuation based on detection of on-coming traffic (Stam, 2001). Depending on roadway conditions such as day/night, rain, snow,

(a) Activating defroster

(b) Windshield icing in freezing rain conditions

Figure 2.12 Windshield defroster button activation.

(a) Lane detection system in a
Volkswagen Golf

(b) Ice obscuring adaptive cruise
sensors

Figure 2.13 ADAS systems and challenges.

and areas of dense fog, the lighting settings can indicate where there may be visibility challenges for the driver or camera-based ADAS (Gallen et al., 2015). Monitoring lighting system function may allow agencies to pro-actively target deployment of speed management tactics, such as variable speed limits.

2.9 Emergency Systems

2.9.1 Hazard Lights

Hazard light activations on roadways typically indicate where vehicles have stopped or slowed due to roadway conditions such as heavy rain, icing, fog, presence of a slowed queue, animals, or vehicle malfunction. This activation can be received from the CAN Bus, and if delivered to a traffic management center would potentially allow agencies to actively monitor roadway hazards using a real-time integrated system.

2.9.2 ADAS and Emergency Systems

Recent developments in ADAS technologies enable vehicles to partially control itself and provide feedback

to the driver using camera-based machine vision or LiDAR-based roadway detection systems (Gotzig & Geduld, 2016; Risack et al., 2000). An example of a lane detection and departure warning system is shown in Figure 2.13a. During conditions where visibility on the sensors is obscured, the deactivation of the ADAS feature may serve as an indication of roadway hazards, such as during heavy icing, snow, or fog conditions (Figure 2.13b). In some more extreme scenarios, such as in the event of a crash, mechanical breakdown, or driver request, some vehicles automatically send data to the cloud to request for assistance (Martin, 1996). There is tremendous potential for enhanced real-time roadway monitoring integrating with these systems to a centralized system at a traffic management center.

2.9.3 Tire Pressure Monitoring

Tire pressure data is capable of providing information on the road's condition. Fast changes of pressure in a tire is a good indication of a vehicle hitting a curb, a pothole, a deep transverse joint or another similar road anomaly. Early identification and location of

these points allows agencies to quickly detect and provide maintenance before receiving reports from the motorists.

Further, this data can be complemented with other CAN bus elements that provide road-condition assessments (e.g., accelerations, pitch, and roll) to provide the most accurate information possible.

3. CAN BUS DATA INTEGRATION

The majority of communications between the different electronic control units (ECUs), sensors, analog-to-digital converters and other nodes inside a vehicle are performed following the CAN serial communications protocol (Hristu-Varsakelis & Levine, 2005). This section provides a high-level description of how this data can be obtained, stored, and accessed.

3.1 Interface

The CAN interface requires a specialized connector or twisted pair and is not directly connectable to computers and other host devices (e.g., smartphones or tablets). For this reason, a vehicle interface (VI) that converts wiring from the vehicle to a host-device standard connector such as a 9-pin serial or USB adaptor is required.

There exists a wide variety of VI devices in the market (e.g., Panda, CANedge2, and ELM 327 to name a few) that are capable of connecting CAN to another, host-device readable protocol. These devices usually connect to the vehicle's OBD-II port located under the vehicle's dashboard, shown in Figure 3.1 (SAE, 1995). Through this port, vehicle data that is transmitted in protocols such as CAN, SAE J1850, or ISO 9141 can be accessed. Pin 6 and 14 are used for the CAN protocol.

Figure 3.2 shows examples of connecting to the OBD-II for CAN communication on a vehicle. An open OBD-II female connector is shown in Figure 3.2a. A wireless adaptor can be plugged into this connector as shown in Figure 3.2b. This particular adaptor acts as a wireless hotspot for other hosts to connect and stream CAN data using a dedicated Python library. Figure 3.2c shows an example of a wired connector (callout i) and CAN interface device (callout ii) that connects to the laptop via USB. Software on the laptop is able to interpret the CAN messages in real-time.

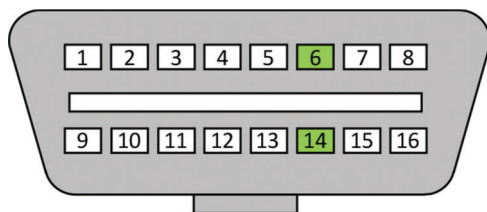If the OBD-II port is not available, access to the CAN network can be performed through accessing the twisted pair itself. In this scenario, special considera-tions are needed to make sure that the interface works at the required voltage and current levels to prevent short circuits from happening (Corrigan, 2016).

3.2 Decoding

A standard CAN message is shown in Figure 3.3 (Hristu-Varsakelis & Levine, 2005). Every message is composed of various frames that allow for a successful transmission. Nevertheless, only two frames are relevant for a higher-level application. The first one is the identifier, also known as arbitration ID (ArbID), which establishes the meaning of the message, indicates its source and specifies its relevance. The second important frame is data, which is the actual information being transmitted (Corrigan, 2016). The VI devices usually come with software that can separate CAN messages into its different frames, allowing users to visualize and manipulate the relevant data.

Once the identifier and data frames have been obtained, it is necessary to decode the data to make it meaningful. A single data frame (up to 64 bits) may contain several signals (Figure 3.4). A signal is composed by a number of bits from the data frame that refer to a specific vehicle variable (e.g., vehicle speed, state of locks, or RPM). These signals may also need to be scaled.

For example, let us suppose that a message with the identifier 0x4D6 was received, and it contained the value 0x000000000000100D in the data frame. The first thing to do would be to identify what information does the 0x4D6 ArbID provide. Then, the proper scaling to the different signals contained in the data frame should be applied. It could be that the 0x10 byte is a signal that refers to the state of the hazard lights and 0x0D could be a signal that refers to the vehicle's speed. In the case of the 0x10 signal, that particular value may indicate that the hazard lights are on, whereas a value of 0x00 may indicate that the lights are off; therefore, no scaling is necessary. Nevertheless, when dealing with the speed signal, 0x0D (13 in decimal) at the time the data was read, it might be required to multiply this value by two to obtain the vehicle's speed in the correct scale.

The original equipment manufacturers (OEMs) define the information regarding what data the different ArbIDs provide, as well as the scaling rules (Menon, 2014). Agreements and partnerships with OEMs can help decode, define, and scale CAN messages using vector database files (DBC). For demonstration purposes, a "cause-and-effect" experiment can be conducted by affecting the vehicle and monitoring the response of the CAN data stream.

The ArbID and the specific signal referring to the wheel-ticks (speed) of the copilot side's wheel of a 2013 Chevrolet Suburban was obtained by such an experiment (Figure 3.5).

- The first step of the process is to read and save all the messages transmitted in the vehicle's CAN network for a period of time without activating the signal that is being searched (Figure 3.5a).

Figure 3.1 OBD-II pinout.

(a) An open OBD-11 connector on a Ford F-150

(b) Comma.ai Panda device with Wi-Fi connectivity

(c) NeoFire IV device connected to a Windows laptop via USB
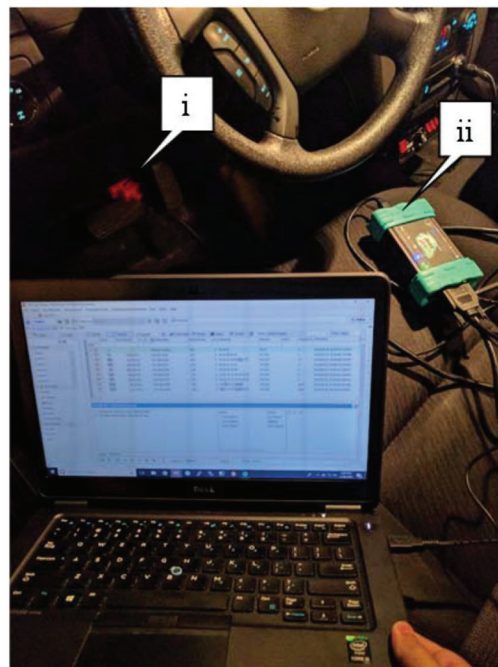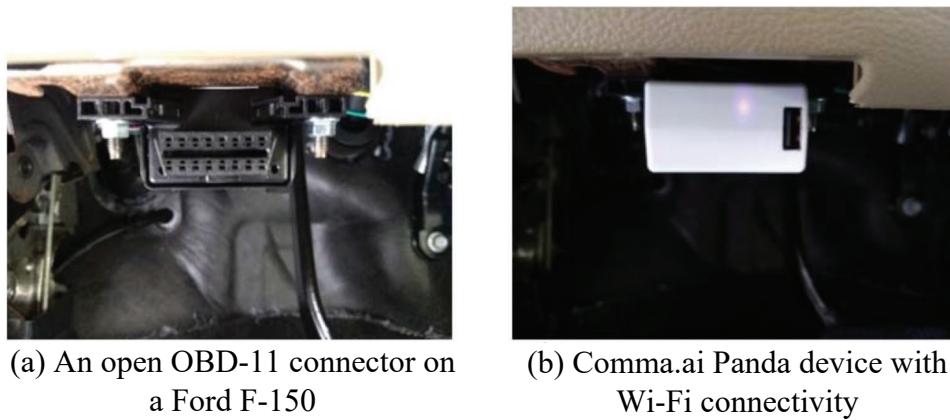
Figure 3.2　OBD-II connector interfaces

S O F	Identifier	R T R	Control	Data	C R C	A C K	E O F

Figure 3.3　Standard CAN message.

- The second step is similar to the first, but it requires the activation of an event that is believed would trigger messages containing the signal. Figure 3.5b shows how a person is manually spinning the wheel, while a file containing all the messages transmitted is saved. After this, the file created in step one (background.csv) and the file created in step two (test1.csv) are compared. ArbIDs that appear in test1.csv, but not in background.csv, are flagged for further analysis.
- In step three, the flagged ArbIDs with their data frames are displayed on real-time to allow for manual testing (Figure 3.5c and Figure 3.5d). At this part of the process, the user can trigger the signal whenever it is convenient and see real-time changes in a computer terminal. Figure 3.5, callouts i and ii, show the result of the reverse-engineering process.

The ArbID containing the copilot's wheel-tick information is 0xC5, whereas the specific signal providing the actual value is the byte inside the red squares (callouts i and ii).

Figure 3.4 Data signals.

(a) Step one: data acquisition without triggering the event

(b) Step two: data acquisition while triggering the event
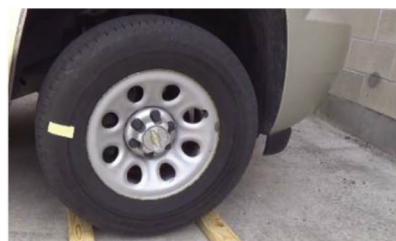
(c) Step three: analysis of interesting ArbIDs without triggering the event

(d) Step three: analysis of interesting ArbIDs while triggering the event

Figure 3.5 Reverse-engineering CAN bus signals.

3.3 Transfer and Storage

There are various ways in which CAN data can be transmitted and saved. As stated in section 3.1, a vehicle's OBD-II port can be utilized to transmit CAN data with the help of a VI device. The CAN data is received at high frequency, often times at 10 or 20 ms intervals depending on the type of message. The VI devices buffer the messages, and then transfer the read data through USB, Bluetooth, or Wi-Fi to another device for processing; or they could save the raw information in SD cards for future analysis. Since there can be hundreds if not thousands of different messages generated from a single vehicle at high frequency, thoughtful consideration is needed as to which of those messages are saved for one or more specific use cases, how often they are saved, and which messages to discard to not overwhelm the processing system.

Once the vehicle's CAN data is received by the host device (laptop, embedded computer, smartphone, or tablet), it can be processed, re-transferred, and/or stored. For example, if a real-time analysis is desired, an embedded computer could process the data and then send the relevant information to a smartphone for display. If real-time analysis is not required, then the host device could simply save the information in a CSV file to process the data later. If the objective is to examine an entire fleet, then the received data by each vehicle could be inserted in a database, which would facilitate a broad analysis. The most efficient transfer and

Figure 3.6 High-level network diagram of possible data transfers.

storage of data will depend on the task's objectives and scope.

Figure 3.6 shows a high-level network diagram with examples of possible data transfers. Not all possible data exchanges are displayed.

3.4 Access

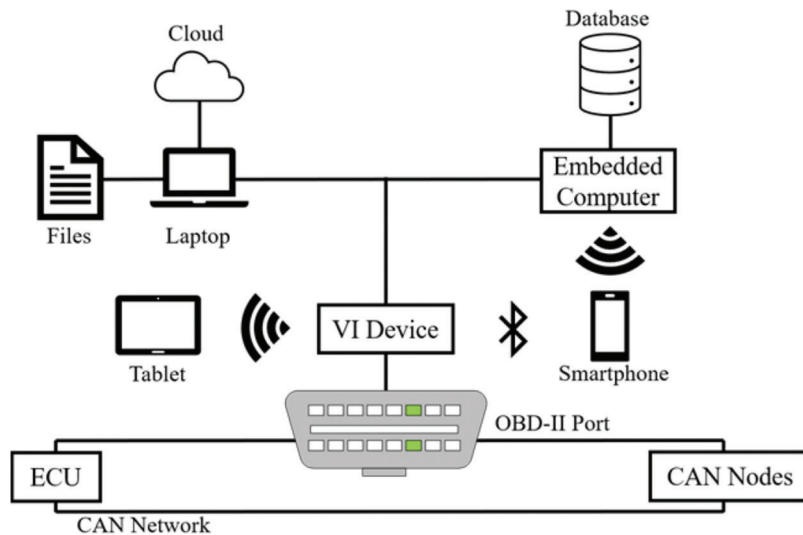Just as there are various options for the transfer and storage of data, there also exists many ways in which it can accessed. If data was stored in a database, the use of queries and database connectivity libraries are necessary to extract specific data. User roles and privileges would need to be defined in the database management system. For CAN data saved in files such as .csv, .xlsx, .txt, or similar, Microsoft Excel or a flat-file reader may suffice for simple viewing on the machine or file system which it is stored. More complex analysis may require using applications written in Python or C++ to read, process, and display the data. If the data received is to be processed and displayed in an online dashboard, access to the site can be public, or by delegating roles and users, and perhaps providing instructions on what set of data is visible to certain groups.

4. WEATHER DATA INTEGRATION

Current sources for assessing winter roadway conditions involve acquiring data from national repositories, agency-maintained mobile and stationary sensors, private weather service providers, field observations, and social media (Gopalakrishna et al., 2016). According to a FHWA report, a poll of 39 states found that all responding departments of transportation had subscribed to at least one type of National Weather Service product in 2015 for weather maintenance and operations (Gopalakrishna et al., 2016). As part of the effort to gradually incorporate vehicle CAN Bus information into winter operation metrics, the current

state-of-the-practice in public weather products, as well as emerging sources, provides high-level assessment, model validation, forecasting, and data supplementation to the emerging vehicle data effort. The following subsections describe four weather data sources that were investigated and incorporated into the project as part of the weather data implementation effort.

4.1 North American Land Data Assimilation System (NLDAS)

NLDAS is a climate and weather dataset provided by NOAA and NASA (Xia et al., 2012). The data is assimilated to 1/8th degree spatial resolution and provides weather variables such as surface skin temperature, solar flux, and precipitation type and rate at 1-hour intervals. In collaboration with Purdue University College of Science, a near real-time data ingestion process populates a database during the winter season (November to March) from which dashboards for after-action reviews and CAN Bus data are integrated. Figure 4.1 shows an integrated dashboard of three plots from NLDAS data during a snow event on December 15, 2019 in the Crawfordsville district. The charts plot wintry precipitation, solar flux, and surface skin temperature over a 48-hour period. The data are presented as interquartile-range (IQR) bars for every hour over all data points in the district.

4.2 Doppler

Doppler data is output from the NOAA National Severe Storms Laboratory (NSSL) Multi-Radar/Multi-Sensor System (MRMS) (NSSL, n.d.). The system offers a variety of products at 1 km spatial resolution and at different temporal frequencies depending on the product. For this research, the Seamless Hybrid Scan Reflectivity (HSR) is used for validating ground truth data and populating dashboards. Seamless HSR is an
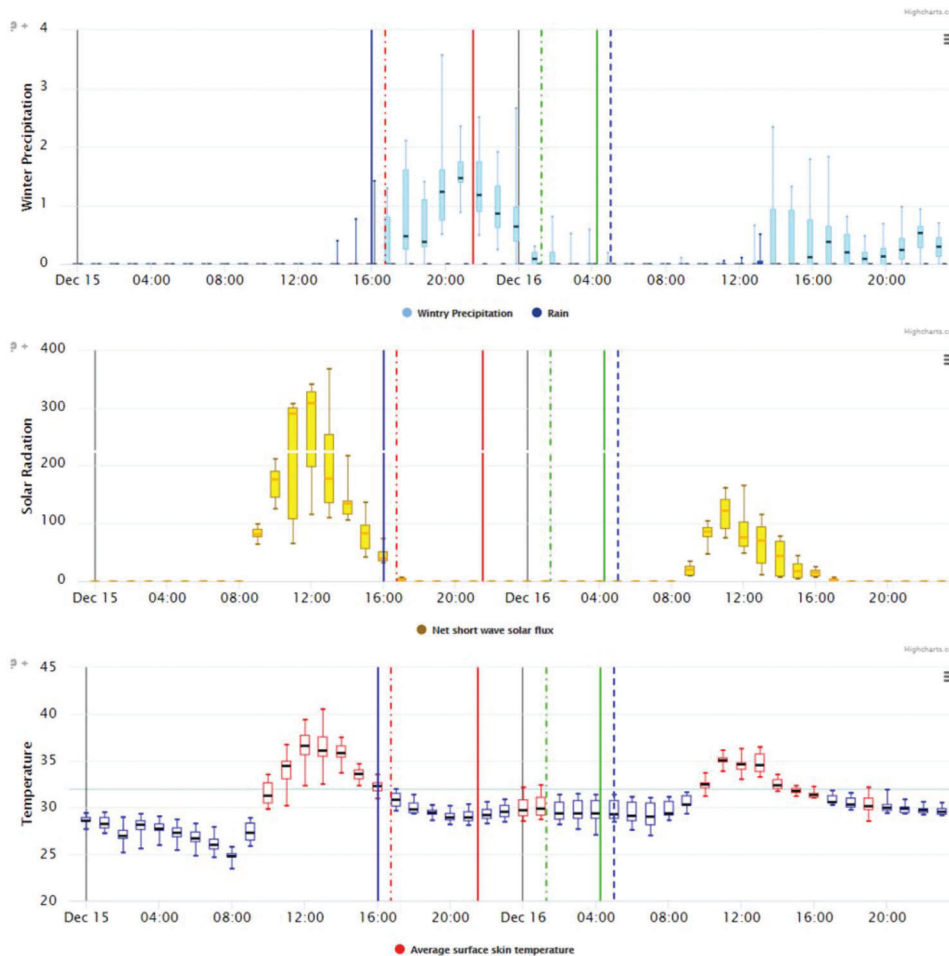
Figure 4.1 NLDAS data for Crawfordsville, December 15–16, 2019.

assimilated product of various radar systems in the continental United States, producing Doppler reflectivity, precipitation type and rate at 2-minute fidelity. The data is provided in GRidded Information in Binary (GRIB) format and is fetched from NOAA repositories via File Transfer Protocol (FTP) (NOAA/National Weather Service, 2010). Figure 4.2 shows an integrated speed map with Doppler overlaid for a severe storm over metro Indianapolis on April 8, 2020. The green and yellow colors indicate trace amounts of precipitation where the orange, red, and purple indicate high reflectivity levels from heavy precipitation or hail. Callout i shows a segment of I-465 on the northwest side of Indianapolis where speeds have dropped below 35 mph as indicated by the orange color highlighting the segment on the map.

4.3 High Resolution Rapid Refresh (HRRR)

The HRRR system is an improvement on the existing Rapid Refresh (RAP) hourly weather data assimilation model and forecast system developed by NOAA (Benjamin et al., 2016). HRRR provides dozens of weather variables at 3 km spatial resolution and

provides forecasting up to 18 hours at 1-hour increments. Figure 4.3 shows an example of surface wind gust data for April 17, 2020 visualized using the NOAA Weather and Climate Toolkit (NOAA, 2020). For the project, each HRRR data point is mapped to a road segment and makes use of the direction of travel to determine the effects of directional weather variables (such as wind) on traffic behavior.

4.4 Mobile Road Weather Information System (MARWIS)

The MARWIS is an infrared system that estimates road friction, snow and ice, water film height, and surface temperature (Bunnell et al., 2016). The device is typically mounted on the rear or side of a vehicle and reports measurements up to 1-second frequency. During the course of the project, MARWIS was collected and reconciled with CAN Bus data during winter road testing to compare, contrast, and verify estimated friction and slip calculated from the vehicle. MARWIS measurements are accurate up to about 50 mph (Bunnell et al., 2016).
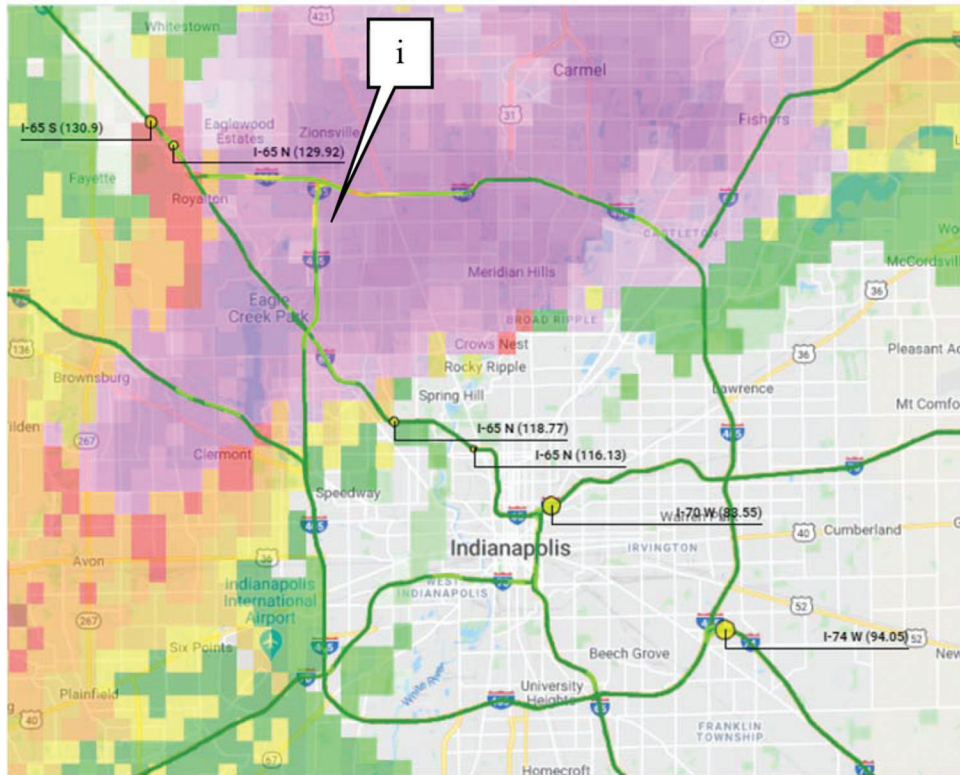
Figure 4.2   Doppler data during severe storm, April 8, 2020.
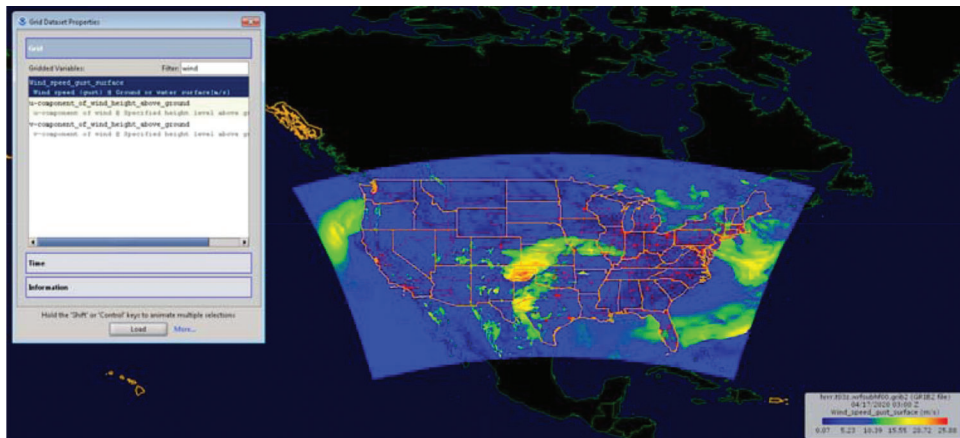
Figure 4.3   Surface wind gust potential using HRRR, April 17, 2020.

5. ENGAGEMENT WITH STAKEHOLDERS

5.1 INDOT

A workshop was conducted in November 2017 with INDOT Research Division and the Traffic Management Center, Purdue researchers, and Intrepid CS, a provider of vehicle networking devices. The workshop gave an overview of some CAN interface technologies and demonstrated capabilities using third-party devices connected to a test vehicle. Some activities of the workshop are highlighted in Figure 5.1.

5.2 Industry Partners

Several engagement activities were conducted with public agencies and industry partners over the duration of the project. The below sub-sections highlight key activities with the stakeholders that have furthered use case development and implementation of the project.

5.2.1 Volkswagen

Researchers engaged with Volkswagen of America Electronics Research Laboratory (VW-ERL) from Q4

Jim Sturdevant testing acceleration signal response on a CAN interface

Figure 5.1 CAN workshop with Intrepid CS, November 2017.

(a) Testing with Audi A4 during winter conditions.
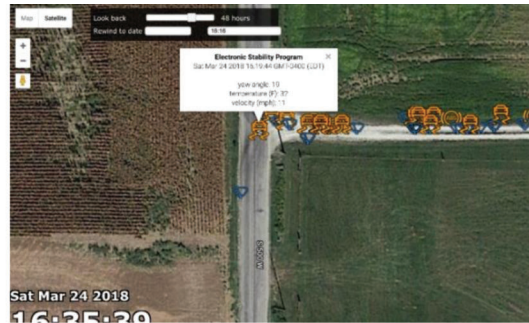
(b) Dashboard showing ABS, traction control intervention, and windshield wiper activation.

Figure 5.2 Enhanced probe data collection with VW-ERL.

2017 through Q4 2018 on developing use cases from data retrieved through the CAN bus. Two cases were implemented and tested in Indiana: Traffic Light Indication (TLI) and enhanced probe data for winter weather applications. A loan vehicle was provided to Purdue during the collaboration. Research outcomes were presented in the FHWA Road Weather Maintenance Meeting in 2018, the TRB 2019 Annual Meeting, 2019 Purdue Road School, and the 2019 AASHTO Maintenance Committee summer meeting. Figure 5.2 shows testing with the Audi A4 Allroad vehicle during winter weather conditions (Figure 5.2a) and corresponding dashboard showing traction control, ABS, and windshield wiper activations from the test (Figure 5.2b). The data is streamed in real time to Purdue hosts for querying by the dashboard.

5.2.2 Nira Dynamics AB

Nira Dynamics AB, based out of Sweden, is known for their innovations in vehicle onboard analytics and road perception. The company employs tire pressure sensors and uses the sensors to gather information about road roughness, potholes and road bumps (Nira Dynamics AB, n.d.). The team is currently exploring potential collaboration opportunities to deploy this innovative technology on a local fleet (Figure 5.3).

5.2.3 Wejo

Enhanced vehicle data from the automotive industry was available for researchers through a collaboration with Wejo. Hard-braking data collected from anonymized consumer vehicles where a deceleration of greater than 0.26 g was retrieved in scale. The dataset contains global coordinates and time stamp for a hard-braking event that occurred. Figure 5.4a shows 1.5 million hard-braking events over a 1-week period in August 2019 within the state of Indiana, with each red dot signifying a hard-braking event. Figure 5.4b illustrates a histogram of the hard-barking events from vehicles travelling above speeds of 45 mph on I-65. Callouts i–iv

(a) INDOT Traffic Management Center, Indianapolis

(b) Discussion with INDOT Seymour district

Figure 5.3 Collaboration with Nira Dynamics AB partners, September 17–21, 2018.
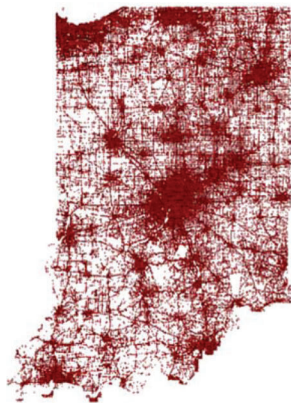
(a) Statewide
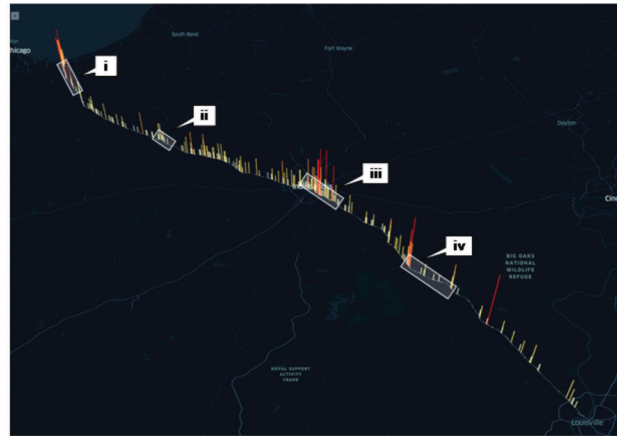
(b) I-65

Figure 5.4 Hard braking events over 1-week period.

represents the active work zones during this period. Potential research applications for hard braking events include identifying safety hazards at work zones, signalized intersections, interchanges and entry/exit ramps. More information can be found in Appendix E.

5.2.4 General Motors

General Motors representatives engaged Purdue researchers and INDOT in January 2019 and January 2020 during the Transportation Research Board Annual Meeting. A number of teleconferences were held between General Motors, INDOT, and Purdue researchers in Q2 2020 to discuss forthcoming collaborative opportunities.

6. WEB PORTALS FOR DATA INTEGRATION

Five dashboard applications were developed for the project by Purdue investigators. One additional dashboard was developed in collaboration with an industry partner. The section below provides a brief overview of the dashboards and the applied use cases.

6.1 Speed Heatmap for Automatic Vehicle Location and Mobile Road Weather Information Sensor

A "heatmap" dashboard integrates traffic speed over miles of interstate routes with built-in snow plow trajectories using Automatic Vehicle Location (AVL) devices and Mobile Road Weather Information Sensor (MARWIS) friction values. Figure 6.1 shows an example speed heatmap with trajectories of friction values collected from a plow truck equipped with MARWIS overlaid for a major winter storm on I-465 on January 12, 2019. Horizontal black lines indicate the locations of INDOT cameras where ground-truthing can be carried out to verify the data.

Callout i shows the trajectory of the plow truck before the storm, where traffic speeds are operating in the 55 to 64 mph range and the friction is detected as "good." Callout ii shows the beginning of the storm where the traffic speeds drop to below 35 mph and the friction starts to deteriorate into the "caution" and "extremely bad" ranges. Callout iii shows where there were challenges after the height of the AM peak has passed but a second band of snow enters the area.
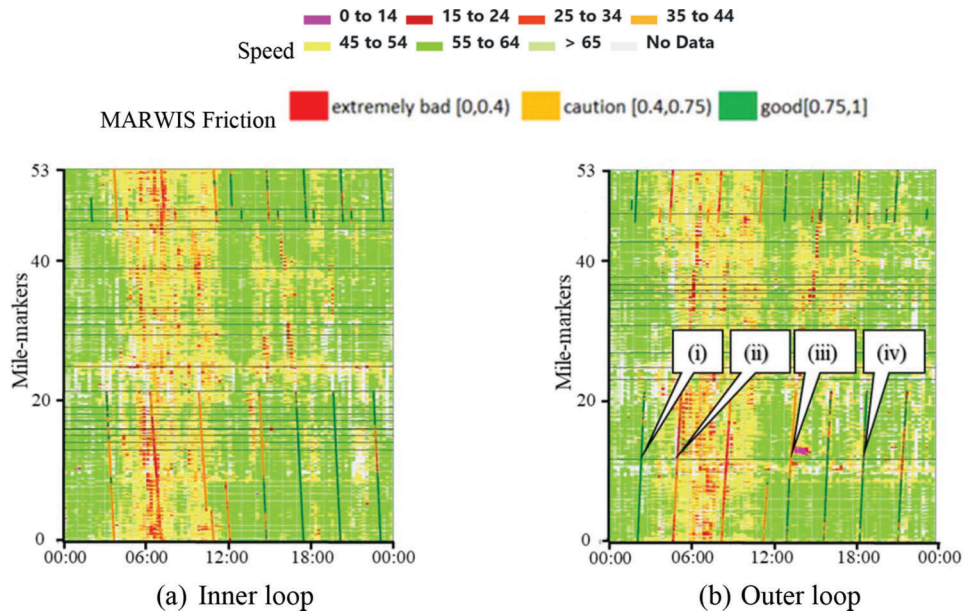
Figure 6.1 Heatmap of traffic speeds with friction overlaid on I-465, January 12, 2019.
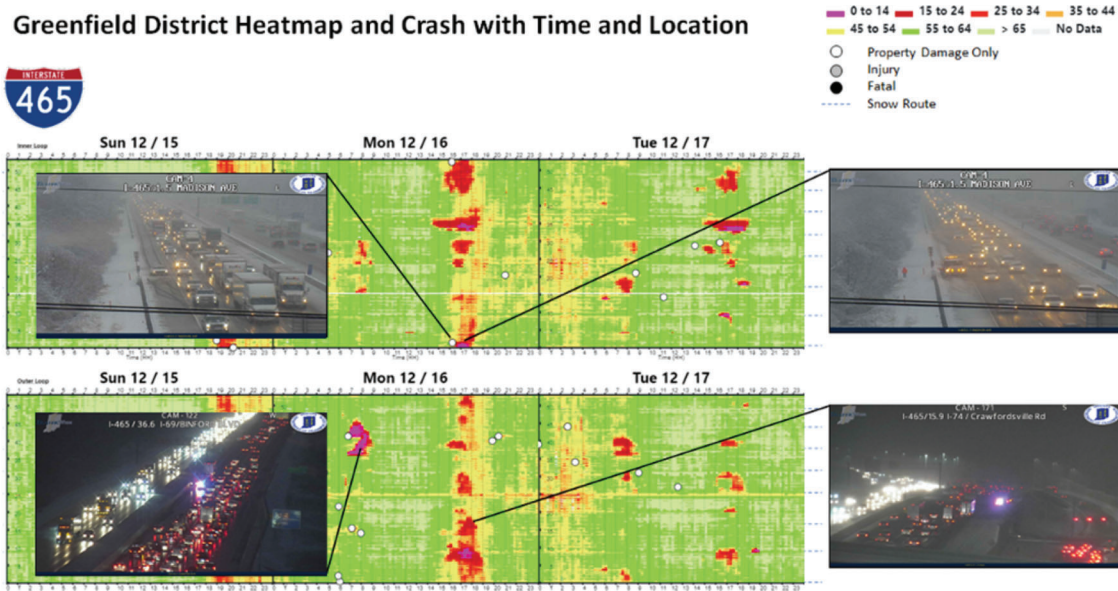
Figure 6.2 Heatmap of traffic speeds with integrated camera images, December 16, 2019.

Finally, callout iv shows a recovery period during the PM peak where both traffic speeds are mostly above 44 mph and the friction has returned to "good."

An example of using the speed heatmap to pull camera images for data verification is shown in Figure 6.2. In this view, 1-minute cached camera images are stored in an SQL database and temporally and spatially aligned to pixels on the heatmap. When the user mouse-overs a pixel, the image at the time and location of the pixel is displayed. Additionally, the heat map populates property damage only (PDO), injury, and fatal crashes with hollow white, gray, and black circles respectively.

6.2 Winter Weather Enhanced Probe Data Map

A web dashboard was developed to plot locations where there was traction control intervention, ABS, harsh acceleration, hazard lights on and off, windshield wipers, temperature, and vehicle heading on a Google Maps overlay. The data was transmitted from a logging computer directly connected to the in-vehicle bus to external servers to process the information for the dashboard. Figure 6.3 shows an example screenshot from the application during an ice storm on I-70 in Missouri. Callout i shows locations where the windshield wipers were activated manually. Callout ii and ii
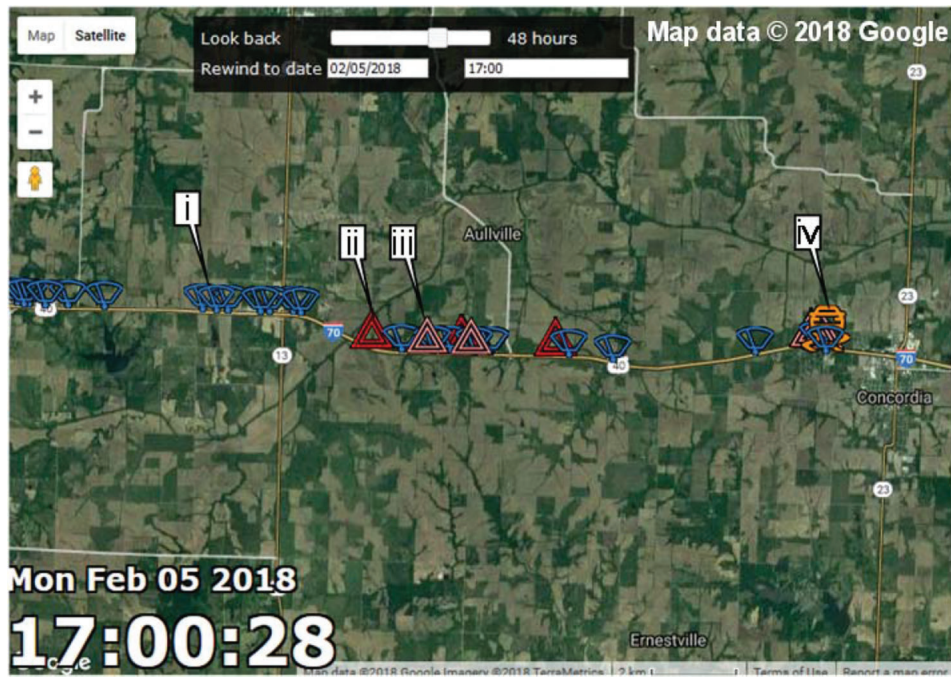
Figure 6.3 Dashboard displaying traction control, ABS, hazard lights, and windshield events during an ice storm on I-70 in Missouri.
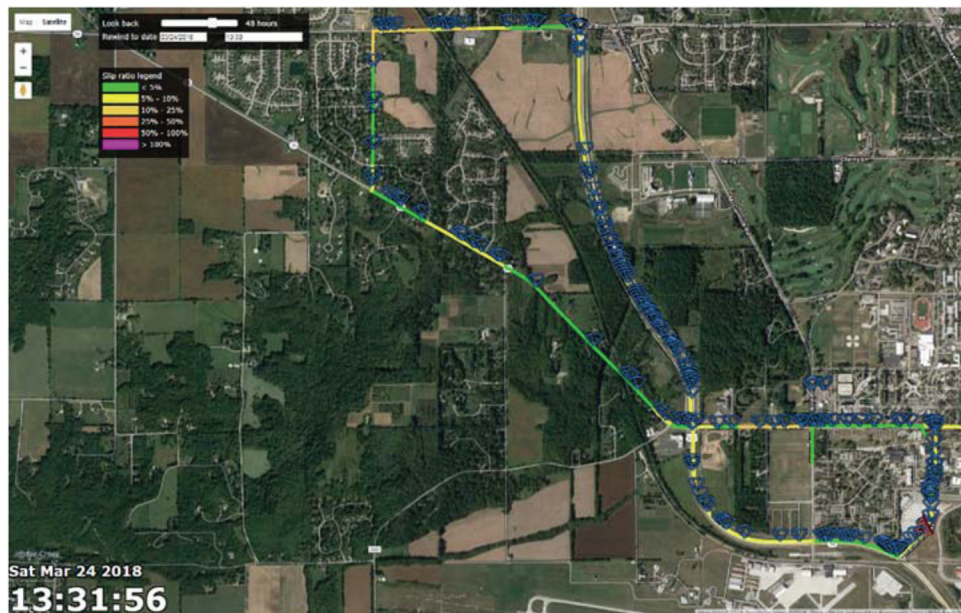
Figure 6.4 Hazardous conditions dashboard with color representing slip ratio of roadway segments.

shows where the hazard lights were turned on, then off during an unsafe driving area. Callout iv shows a location where the traction control system intervened. The dashboard works in real-time as well as having the ability to look at historic data.

The dashboard can also visualize the amount of slip experienced by the vehicle on segments of roadway. Slip is measured by taking individual wheel speeds of a single vehicle and computing the absolute maximum difference any single wheel is experiencing from the others.

Figure 6.4 shows an example of the dashboard with colored segments of roadway, with green being good friction to red and pink to slippery conditions, this shows the road conditions while driving in a loop near Purdue campus during a snow event on March 24, 2018.

6.3 High-Fidelity Weather Heatmap

A near-real-time dashboard was developed to integrate NOAA High-Resolution Rapid Refresh (HRRR)
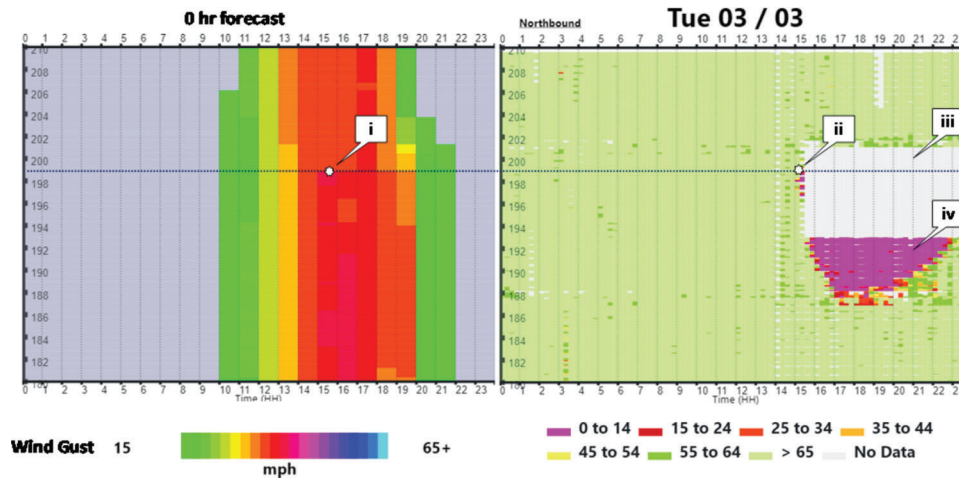
Figure 6.5 High-fidelity weather heatmap showing wind gusts alongside traffic speeds, March 3, 2020.
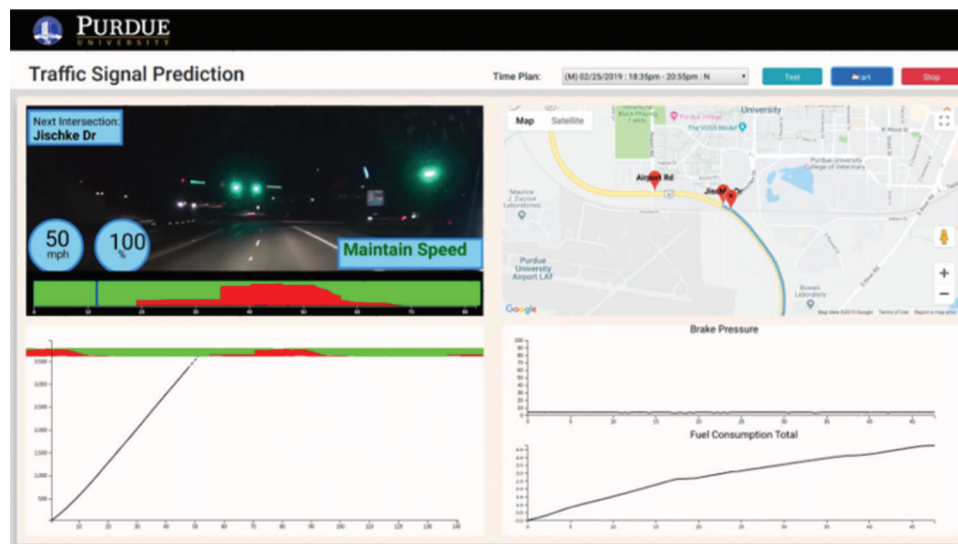
Figure 6.6 Integrated fuel consumption estimation and brake pressure dashboard.

data alongside traffic speeds. The dashboard can display 24 different weather variables including wind speed and direction, visibility, and solar radiation per forecast, aligned to interstate routes at 3 km resolution. Figure 6.5 shows the dashboard for a wind event on March 3, 2020 on I-65. The chart on the left shows the wind gust speed for the 0th hour (most up-to-date) forecast between mile marker 180 and 210. Callout i indicates the crash location of three semi-trucks due to high winds at mile 199. This is also reflected on the right-hand traffic speed heatmap (crash location at callout ii). The route was shut down after the crash (callout iii) causing a 5-mile queue (callout iv).

6.4 Integrated Fuel Consumption, Brake Pressure, and Traffic Signal Prediction Application

A real-time dashboard was developed integrating brake pressure, fuel consumption calculated from the mass airflow, and cruise control speed data from the

CAN Bus. The dashboard matches a vehicle's current trajectory with an approaching traffic signal. Using historical phase probability information from the signal controller, the application is able to display the current vehicle's speed, green probability at arrival to the next intersection based on time-of-day and day-of-week, integrated with cruise control speed (if active) and audible speed advisory and stop-or-go decision, brake pressure, and cumulative fuel consumption. Figure 6.6 shows a screen capture from the dashboard for a vehicle on travelling along US-231 in West Lafayette during actuated-coordinated operation. There is also an option to fully integrate the dashboard with video input.

6.5 District-Level Vehicle Utilization

A management-level dashboard was developed to monitor vehicles equipped with AVL at a district level. Data from GPS-embedded computers and speed heuristics determine activity type and duration for any
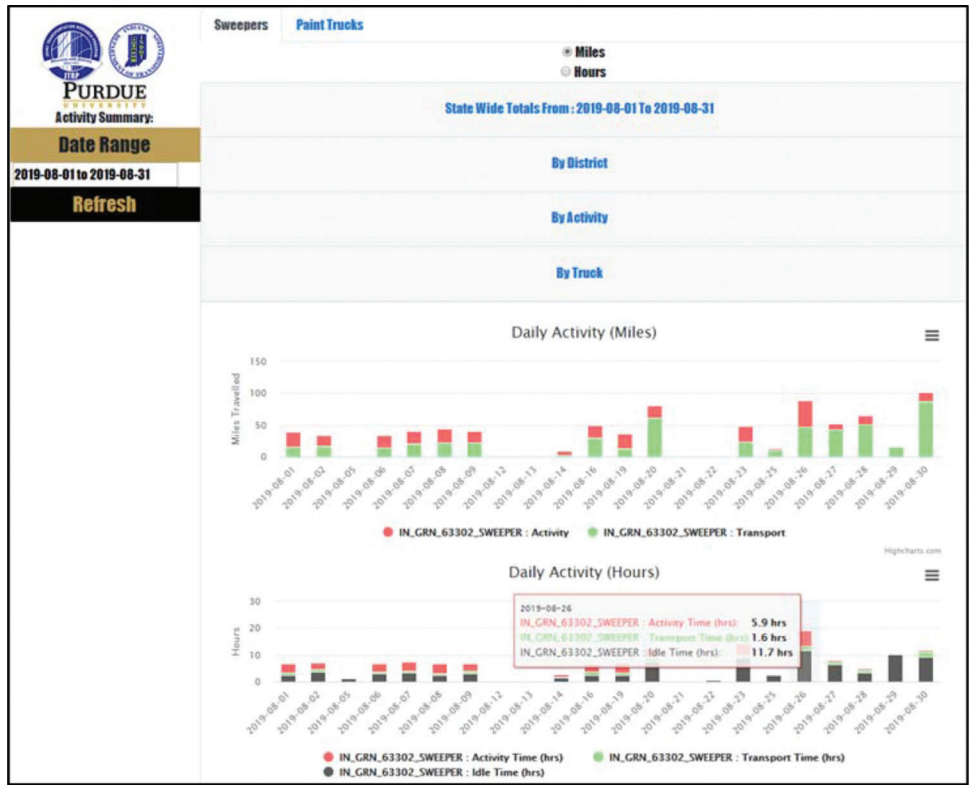
Figure 6.7 District-level vehicle utilization dashboard.

Figure 6.8 Daily utilization dashboard for a single maintenance vehicle.

equipped vehicle. Figure 6.7 shows a screen scrape of vehicle utilization between May 2019 and January 2020 for AVL-equipped sweepers in Greenfield district. Graphs from the dashboard track total miles driven and hours operated by day per district. High-level views make use of pie charts to monitor utilization of all vehicles across the six districts. A drill-down feature allows a per-vehicle view, as seen in the Gantt chart in Figure 6.8, which tracks the daily hours actively working, in transport, or idling.

7. DEPLOYMENT

7.1 Single Vehicle Pilot

A pilot system to implement CAN Bus data into a real-time dashboard for one vehicle was developed as part of this project. The VI used for the implementation was Comma.ai's Panda device to receive CAN messages from the vehicle and stream the data to an external device via Wi-Fi (Figure 3.2). A Raspberry Pi embedded computer on the vehicle receives the stream from Panda and decodes signals of interest using pre-installed DBC files (Figure 7.1). The computer also transforms the data into a format that can be saved locally on the device or can be transmitted over cellular network to endpoints on external servers.

Figure 7.2 shows the architecture for the pilot system. From within the vehicle the embedded computer sends the transformed data over 4G or 5G networks, through the cloud, to be displayed on a web interface. The protocol used for this pilot is HTTP and the formatting of the data is structured in JSON.

A series of pilot tests were performed on the following dates listed in Table 7.1 over the duration of the project.

Figure 7.1 Raspberry Pi device for receiving CAN messages from Wi-Fi.

7.2 At Scale

There are a number of considerations for a scale-out deployment of a CAN Bus data collection, integration, and visualization system. As discussed in Section 3.3, a single vehicle can potentially generate thousands of messages per second and each use case requires which of those messages are to be captured by the system. When this process is scaled out to a fleet level, the capacity of the agency's network and servers (whether they be hosted on premise or in the cloud) to handle the number of transactions becomes critical.

To reduce data size and load on the system, it is recommended to save only CAN Bus messages that are necessary to generate agency performance measures, such as those defined in Section 2. Once the subset of messages is determined, the frequency of data capture and method of transformation and transmission of the data to the agency is designed so that the system operates within acceptable threshold for latency given the network constraints and handles the volume of data transactions effectively incoming to the agency. The following subsections describe the methods at the vehicle and system level that can streamline the process, and potential collaborations with vendors and manufacturers that can facilitate deployment of off-the-shelf products.

7.2.1 In-Vehicle Considerations

To make data collection more scalable, the following features can be implemented at the vehicle level to reduce the size of the data before uploading to the agency's servers.

- *Save only necessary signals.* To cut down the number of messages collected, save only the signals necessary for generating metrics.
- *Limit how often each signal is sampled.* For each signal, determine the minimum frequency it needs to be saved to produce metrics. For instance, it may suffice to collect GPS data every 3 seconds for tactical deployment of snow plows, but to calculate slipping on the roadway it
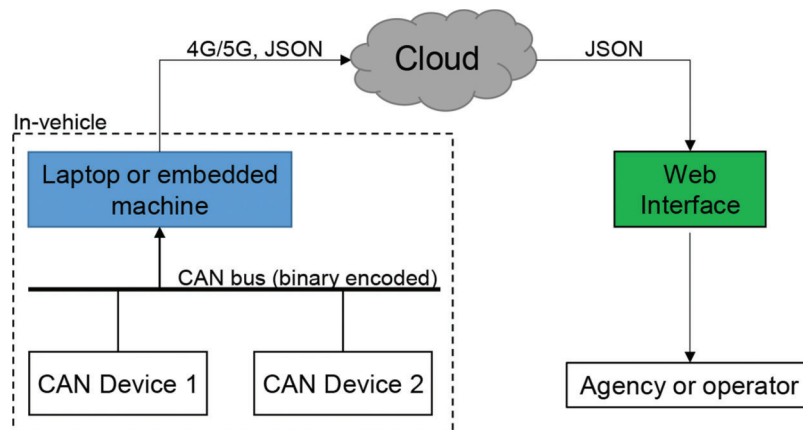

Figure 7.2 System architecture for pilot system.

TABLE 7.1
Pilot testing dates

Testing Date	Data Elements Tested
February 5, 2018	Hazard lights, windshield wipers, traction control system, ABS, ambient temperature
February 10, 2018	Windshield wipers, traction control system, ABS, ambient temperature
February 11, 2018	Windshield wipers, traction control system, ABS, ambient temperature
February 17, 2018	Windshield wipers, traction control system, ABS, ambient temperature
March 25, 2018	Hazard lights, windshield wipers, wheel counters, ABS, ambient temperature, steering angle, brake pressure
April 8, 2018	Wheel counters
May 16, 2018	Steering angle
June 14, 2018	Lateral acceleration, steering angle, wheel counter, RPM
June 17, 2018	Wheel counter
January 9, 2019	Defroster, climate control, lighting systems, windshield wiper, brake pressure, accelerometer, traction control system, ABS, wheel counter, two-/four-wheel drive system
January 25, 2019	Lateral acceleration
May 1, 2019	Lateral acceleration, brake pressure

may be necessary to receive wheel speed signals at 10 to 100 ms if the vehicle is moving at high speed.

- *Transform and reduce high-frequency signals into insights.* Some signals need to be transformed before it becomes meaningful. For instance, a large amount of wheel speed messages is generated very quickly at 10 to 100 ms but the majority of the time the data does not provide anything more insightful than vehicle speed. If the practitioners only want to know when a vehicle experienced slipping, pairs of consecutive wheel speed messages can be compared at each receive interval and only when a large sudden increase in speed is detected on one wheel, the message is then saved. All other messages are discarded to reduce overhead.
- *Reduce scalar values into Boolean using thresholds when feasible.* Some events only need a true or false representation even though the vehicle may generate a scalar value. For example, accelerometer messages are typically represented in meters-per-second-squared and are generated at high-frequency. However, if only road quality is of concern, a threshold can be set for the vertical acceleration component so that when the threshold is exceeded, a "true" value is saved that would represent a strong vertical acceleration, as a signature for a potential pothole or transverse joint.
- *Aggregate multiple data elements.* Some CAN messages can be combined to capture a specific type of an event. Once the event is detected, the underlying CAN messages can be discarded. For example, to determine hard braking on the roadway, a combination of high brake pressure, rapid change in speed, and spike in longitudinal acceleration can be synthesized into a single event.
- *Compress the data.* Before sending the data over the network, messages should be compressed to reduce data size.
- *Save data in an efficient format.* Some data formats such as XML carry more overhead than other formats like JSON, CSV, or binary encoding (Maggiore, 2019).

7.2.2 Network and Server Considerations

Network latency is determined by the type of cellular connectivity and capacity to process and store data is dependent on the hardware and software configuration of agency's servers, whether it be on premise or hosted in the cloud. The combination of the two factors determines how many vehicles can be processed by the system in real-time.

A previous study has demonstrated 4G-LTE cellular network speed in a moving vehicle has the capability to transmit at 10 Mbps (Mosyagin, 2010). While a seemingly large number of messages can be sent when the connection is good, this does not consider conditions in rural areas with sparse connectivity. This also does not consider overhead that is required to negotiate the transmission of each data packet (Maggiore, 2019). MQTT services such as Apache Kafka (Apache Software Foundation, 2020) and Google Pub/Sub (Google, 2020) make use of efficient protocols to transport data between devices and server hosts and ensures data consistency in high-latency environments (Robinson et al., 2005). These services allow publishers that generate the data (the vehicles) and subscribers that consume the data (the servers) to negotiate message delivery with small overhead and high resilience to dropped connections, compared to web protocols such as HTTP (flespi, 2018).

For on-premise servers, data storage capacity, and throughput are important considerations when implementing a real-time data collection and reporting system at the agency. The storage capacity of these systems must meet the demand of the volume of data per unit time (i.e., data velocity) uploaded from all vehicles. In addition, database systems rely heavily on the throughput speed of the storage device; the faster the storage, the greater number of transactions can be performed to store CAN messages (Regola, 2012). For hosting in cloud services, computing and storage resources can be scaled quickly, but can be costly for moving and storing large volumes of data to and from the cloud (Tak et al., 2020).

7.2.3 Leveraging Off-the-Shelf Products

There are many off-the-shelf products that integrate OBD-II CAN interface with cloud services. Some telecommunication providers such as Verizon sell packaged

VI connectors and GPS-enabled devices to relay signals such as location, key on and off, odometer, and basic diagnostic trouble codes (DTC) for maintenance (Aries, 2020). Figure 7.3a shows an example of a 9-pin J-connector interface (callout i) that sends CAN information to an embedded device (callout ii). Figure 7.3b shows an example of the interface for tracking one vehicle on a web dashboard.

Furthermore, select vehicle manufacturers, equipment vendors, and even insurance companies have developed products to integrate enhanced CAN Bus messages with the cloud directly (Barabba et al., 2002; Ford Media Center, 2015; Progressive, n.d.). These embedded VI devices work with high-frequency CAN data and transmit messages to a designated service provider for supported vehicles. Depending on the product, the CAN data can be decoded for messages pertaining to the vehicle for certain makes and models. There are opportunities to leverage these off-the-shelf devices for retrieving data for quick deployment.

Original equipment vendors such as Nira Dynamics AB have developed integrated road condition monitoring systems built into production vehicles in collaboration with manufacturers (NIRA Dynamics AB, 2017). The data is received and processed on board the vehicle and using the vehicle's integrated cellular connection then uploaded to a web platform for real-time road condition diagnostics. An example of the dashboard is displayed in Figure 7.4 during a storm around Purdue's campus on December 16, 2019.

7.3 Integration into District and Sub-District Activities

After-action reports for the 2018–2019 and 2019–2020 winter seasons were produced, and a number of workshops at INDOT districts were conducted over the course of the project. The below subsections detail the action-items and activities over the course of the project.

(a) 9-pin J-connector for snow plows
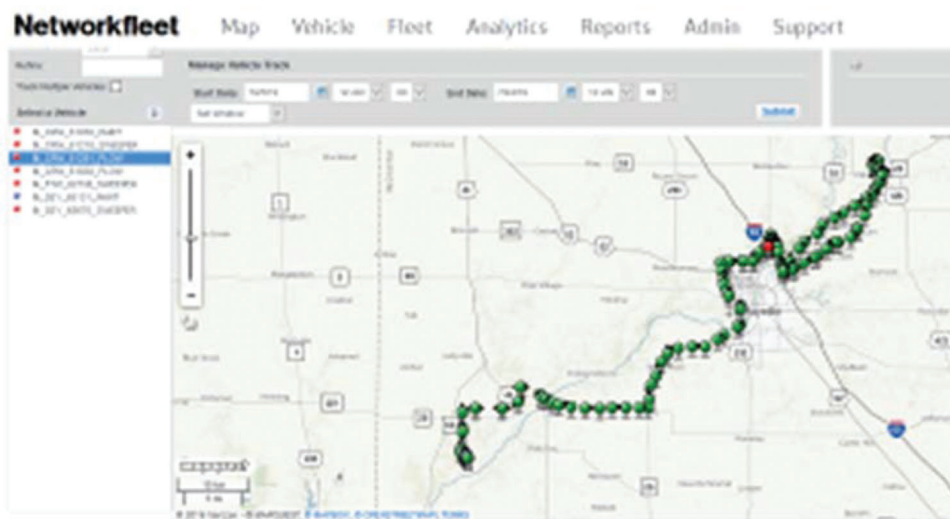
(b) Web dashboard

Figure 7.3 Verizon NetworkFleet system.
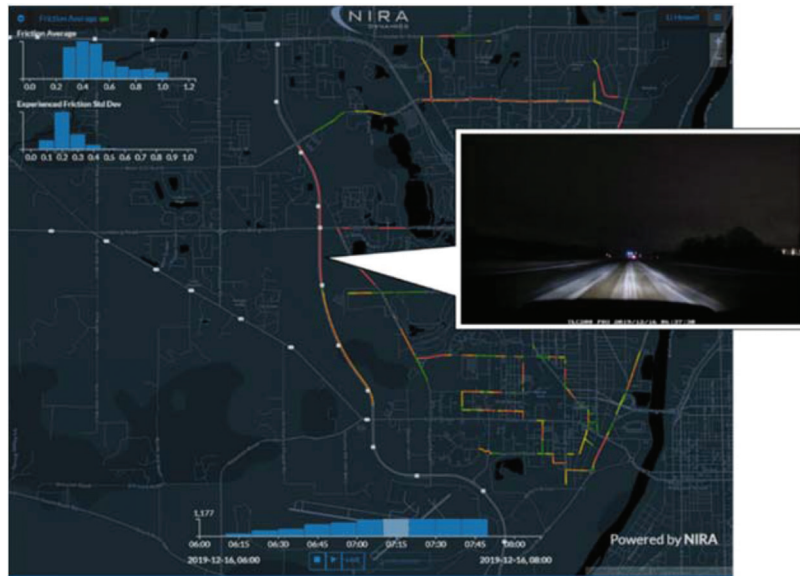
Figure 7.4 Nira dynamics AB road surface information (RSI) tool.
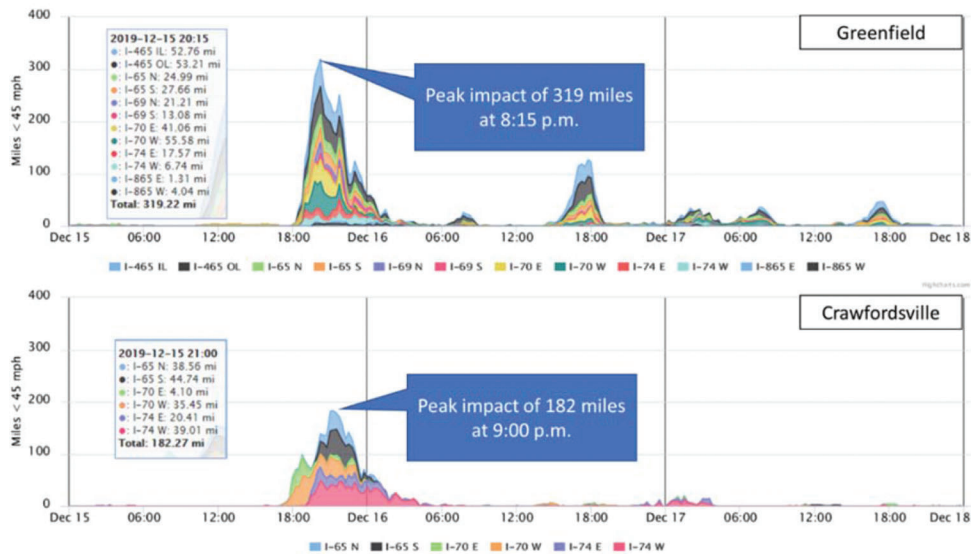
Figure 7.5 After-action report summary for Greenfield and Crawfordsville districts, December 15, 2019.

7.3.1 After-Action Reports

For each winter storm over the duration of the project, an after-action report was prepared using the developed applications and data sources. The reports contain a traffic speed and weather "ticker" graphic showing district and state-wide impacts (Figure 7.5), Doppler radar map, connected vehicle, MARWIS and AVL data, where available. Table 7.2 shows a summary of the miles impacted by each storm statewide for the after-action reports produced.

7.3.2 Workshops

A number of workshops were held during the 2019–2020 winter season to disseminate information regarding applications that were developed from the research, and to discuss after-action case studies of recent storms that have recently occurred at that time around the engagement. Dates and locations of the engagements are listed in Table 7.3. Select photos of engagements for a number of district and subdistrict locations are shown in Figure 7.6.

TABLE 7.2
Summary of winter impacts by storm

Storm Date	Peak Impact (miles below 45 mph)
January 12, 2019	181
January 19, 2019	695
January 28, 2019	171
January 31, 2019	427
February 10, 2019	174
February 12, 2019	141
March 30, 2019	231
November 11, 2019	374
November 23, 2019	85
December 15, 2019	576
January 17, 2020	137
February 5, 2020	251

TABLE 7.3
Engagements with INDOT districts

Location of Workshop	Date
West Lafayette Subdistrict	October 22, 2019
Fort Wayne District	December 12, 2019
Seymour District	December 17, 2019
Vincennes District	January 29, 2019
La Porte District	February 4, 2020
Greenfield District	February 20, 2020

(a) West Lafayette Sub, October 22, 2019   (b) Fort Wayne, December 12, 2019

(c) La Porte, February 4, 2020   (d) Greenfield, February 20, 2020

Figure 7.6   Select workshops conducted with INDOT districts and subdistricts.

8. SUMMARY AND RECOMMENDATIONS

Over the course of the project, the research team engaged a number of industry partners to collaborate, consult expertise, test equipment, and share findings of the research with stakeholders. Vehicles from three different manufacturers were used for testing CAN data elements in nine categories. A system for receiving, transmitting and processing the CAN data was piloted using a vehicle interface (VI) with an embedded computer, cellular networks, and back-office data system at Purdue University. A series of dashboards for transforming and displaying the data were developed as part of the user interface deliverables.

A number of workshops engaging INDOT district and subdistrict personnel were conducted over the course of the project to share tools, reports, and research developed from the project. A component of the engagements included after-action reports that were developed specific to each district to give an overview of the roadway performance after each winter storm.

Major recommendations for implementation from this study include the following:

1. Near-term (6–18 months):

   a. Develop relationships with CV data providers to integrate hard braking events into TMC operations.
   b. Develop relationships with CV data providers to integrate loss of friction data (ABS or traction control) into TMC operations and coordinate with winter weather maintenance colleagues.
   c. Develop relationships with CV data providers to identify locations of pavement distress or work zone irregularities using vehicle pitch, roll, and steering.

2. Medium-term (18 months or longer):

   a. Evaluate the feasibility of capturing weather-related data such as windshield wipers, defroster settings and temperature readings to enhance TMC and winter weather management activities.
   b. Develop plans to integrate this data into business processes used by central office, districts, sub-districts and units. The winter weather data is particularly valuable to sub-districts and units.

As vehicles begin to know more about the state of the infrastructure than agencies, there will be huge benefits both for transportation agencies and the automotive industry to partner in developing scalable systems to make use of the CAN Bus data. By enabling enhanced real-time road conditions to be available, there will be tremendous gains in both efficiency and safety. The recommendations from this report and the lessons learned from the early use cases will aid Indiana to become an important stakeholder and help shape this emerging enhanced road condition monitoring using CAN Bus data.

REFERENCES

Alessandroni, G., Klopfenstein, L. C., Delpriori, S., Dromedari, M., Luchetti, G., Paolini, B. D., Seraghiti, A., Lattanzi, E., Freschi, V., Carini, A., & Bogliolo, A. (2014, August). *SmartRoadSense: Collaborative road surface condition monitoring* [Paper presentation]. Eighth International Conference on Mobile Ubiquitous Computing, Systems, Services and Technologies, Rome, Italy. https://doi.org/10.13140/RG.2.1.3

Apache Software Foundation. (2020). *Apache Kafka* [Computer software]. Retrieved May 13, 2020, from https://kafka.apache.org/intro

Aries, K. (2020, October 30). *On-board diagnostics: What you need to know.* Retrieved May 14, 2020, from https://www.verizonconnect.com/resources/article/on-board-diagnostics-obd/

Armantrout, K. M., & Dick, W. M. (1971). *Torque-biasing full-time four-wheel drive for passenger & utility vehicles* (SAE Technical Paper 710614). https://doi.org/10.4271/710614

Barabba, V., Huber, C., Cooke, F., Pudar, N., Smith, J., & Paich, M. (2002, February 1). A multimethod approach for creating new business models: The General Motors onstar project. *INFORMS Journal on Applied Analytics*, *32*(1), 20. https://doi.org/10.1287/inte.32.1.20.18

Benjamin, S. G., Weygandt, S. S., Brown, J. M., Hu, M., Alexander, C. R., Smirnova, T. G., Olson, J. B., James, E. P., Dowell, D. C., Grell, G. A., Lin, H., Peckham, S. E., Smith, T. L., Moninger, W. R., Kenyon, J. S., & Manikin, G. S. (2016, April 1). A North American hourly assimilation and model forecast cycle: The rapid refresh. *Monthly Weather Review*, *144*(4), 1669–1694. https://doi.org/10.1175/MWR-D-15-0242.1

Bunnell, W., Krohn, D., Mathew, J. K., McNamara, M., Mekker, M., Richardson, L., & Bullock, D. M. (2016, March). *Evaluation of mobile advanced road weather information sensor (MARWIS) by Lufft for Indiana Winter Road Operations* [Poster presentation]. Purdue Road School. https://docs.lib.purdue.edu/roadschool/2016/posters/5/

Buttlar, W. G., & Islam, M. S. (2014, November). *Integration of smart-phone-based pavement roughness data collection tool with asset management system* (NEXTRANS Project No. 098IY04). https://www.purdue.edu/discoverypark/nextrans/assets/pdfs/098IY04%20Integration%20of%20Smartphone-Based-Pavement%20Roughness%20data%20collection%20tool%20with%20asset%20management%20system.pdf

Corrigan, S. (2016). *Introduction to the controller area network (CAN)* [PDF file]. https://www.ti.com/lit/an/sloa101b/sloa101b.pdf?ts=1609259808809&ref_url=https%253A%252F%252Fstartpage.com%252F

Elmore, K. L., Flamig, Z. L., Lakshmanan, V., Kaney, B. T., Farmer, V., Reeves, H. D., & Rothfusz, L. P. (2014). MPING: Crowd-sourcing weather reports for research. *Bulletin of the American Meteorological Society*, *95*(9), 1335–1342. https://doi.org/10.1175/BAMS-D-13-00014.1

FHWA. (2017, February 1). *Citizen reporting of current road conditions: Experiences at five state departments of transportation* [Webpage]. Federal Highway Administration. Retrieved May 15, 2020, from https://ops.fhwa.dot.gov/weather/best_practices/citizenreportingcrc/index.htm.

flespi. (2018, January 23). *HTTP vs MQTT performance tests* [Webpage]. Retrieved May 13, 2020, from https://flespi.com/blog/http-vs-mqtt-performance-tests

Ford Media Center. (2015, January 6). *Mobility experiment: Big data drive, Dearborn.* Retrieved May 13, 2020, from https://media.ford.com/content/fordmedia/fna/us/en/news/

2015/01/06/mobility-experiment-big-data-drive-dearborn. html

Gallen, R., Cord, A., Hautière, N., Dumont, É., & Aubert, D. (2015). Nighttime visibility analysis and estimation method in the presence of dense fog. *IEEE Transactions on Intelligent Transportation Systems*, *16*(1), 310–320. https://doi.org/10.1109/TITS.2014.2331177

Google. (2020, November 17). *What is pub/sub?* [Webpage]. Retrieved May 13, 2020, from https://cloud.google.com/pubsub/docs/overview

Gopalakrishna, D., Martin, L., & Neuner, M. (2016, January). *2015 Road weather management performance measures survey, analysis, and report* (Publication No. FHWA-HOP-16-001). Federal Highway Administration. https://ops.fhwa.dot.gov/publications/fhwahop16001/fhwahop16001.pdf

Gotzig, H., & Geduld, G. (2016). Automotive LIDAR. In Winner, H., Hakuli, S., Lotz, F., & Singer C. (Eds.), *Handbook of driver assistance systems: Basic information, components and systems for active safety and comfort* (pp. 405–430). Springer International Publishing.

Groh, E. (1997, February 24). *Intelligent lighting* (SAE paper 970645). SAE International. https://doi.org/10.4271/970645

Hanson, T., Cameron, C., & Hildebrand, E. (2014, September). Evaluation of low-cost consumer-level mobile phone technology for measuring international roughness index (IRI) values. *Canadian Journal of Civil Engineering*, *41*(9), 819–827. https://doi.org/10.1139/cjce-2014-0183

Hristu-Varsakelis, D., & Levine, W. S. (Eds.). (2005). *Handbook of networked and embedded control systems.* Birkhäuser. https://doi.org/10.1007/b137198

Islam, S., Buttlar, W., Aldunate, R., & Vavrik, W. (2014). Measurement of pavement roughness using Android-based smartphone application. *Transportation Research Record: Journal of the Transportation Research Board*, *2457*(1), 30–38. https://doi.org/10.3141/2457-04

Maggiore, G. (2019, January 3). *Profiling the hidden costs of JSON and HTTP(S)*. Medium. https://medium.com/@giuseppemaggiore/profiling-the-hidden-costs-of-json-and-https-c8f327d5db89

Martin, N. (1996). Look to the Sky: Automakers plug into automatic communication systems. *Automotive Industries*, *179*(3), 174–175.

Menon, C. J. (2014, March). *Decoding data from a vehicle's CAN network*. CAN Newsletter, 12–15. https://can-newsletter.org/uploads/media/raw/650082eaec8166fa96e2192d2b1d1bee.pdf

Moran, J. H., & Grimm, R. A. (1971, February 1). *Max trac—Wheel spin control by computer* (SAE Technical Paper 710612). SAE International. https://doi.org/10.4271/710612

Mosyagin, J. (2010). *Using 4G wireless technology in the car.* 12th International Conference on Transparent Optical Networks. Institute of Electrical and Electronic Engineers. https://doi.org/10.1109/ICTON.2010.5549094

NIRA Dynamics AB. (2017, February 23). *New slip hazard warning feature from NIRA Dynamics improves the safety of connected vehicles*. Retrieved May 14, 2020, from https://www.prnewswire.com/news-releases/new-slip-hazard-warning-feature-from-nira-dynamics-improves-the-safety-of-connected-vehicles-614593053.html

Nira Dynamics AB. (n.d.). *Road surface information* [Webpage]. Retrieved April 22, 2020, from https://niradynamics.se/road-surface-information/

NOAA. (2020, June 9). *NOAA's weather and climate toolkit* [Computer software]. Retrieved April 20, 2020, from https://www.ncdc.noaa.gov/wct/index.php

NOAA/National Weather Service. (2010, December 2). *NOMADS-NOAA operational model archive and distribution system* [Webpage]. Retrieved April 20, 2020, from https://nomads.ncep.noaa.gov/

NSSL. (n.d.). *Multi-radar/multi-sensor system (MRMS)* [Webpage]. The National Severe Storms Laboratory. Retrieved April 20, 2020, from https://www.nssl.noaa.gov/projects/mrms/

Progressive. (n.d.). *Get snapshot from Progressive* [Webpage]. Retrieved May 26, 2020, from https://www.progressive.com/auto/discounts/snapshot/

Regola, N., Cieslak, D. A., & Chawla, N. V. (2012, June). The constraints of magnetic versus flash disk capabilities in big data analysis. *ASBD '12: Proceedings of the 2nd Workshop on Architectures and Systems for Big Data*. Association for Computing Machinery. https://doi.org/10.1145/2379436.2379437

Risack, R., Moehler, N., & Enkelmann, W. (2000). Video-based lane keeping assistant. *Proceedings of the IEEE Intelligent Vehicles Symposium 2000*. Institute of Electrical and Electronic Engineers. https://doi.org/10.1109/IVS.2000.898369

Robinson, J. M., Frey, J. G., Stanford-Dark, A. J., Reynolds, A. D., & Bedi, B. V. (2005). Sensor networks and grid middleware for laboratory monitoring. *First International Conference on e-Science and Grid Computing*, *1*, 562–569. http://dblp.uni-trier.de/db/conf/eScience/eScience2005.html#RobinsonFSRB05

SAE. (1995, January). *SAE J1962: Diagnostic connector equivalent to ISO/DIS*. Society of Automotive Engineers. https://law.resource.org/pub/us/cfr/ibr/005/sae.j1962.1995.pdf

Stam, J. S. (2001). *Automatic vehicle high-beam headlamp control system* (SAE Technical Paper 2001-01-0318). SAE International. https://doi.org/10.4271/2001-01-0318

Tak, B. C., Urgaonkar, B., & Sivasubramaniam, A. (2020). *To move or not to move: The economics of cloud computing* [Paper presentation]. 3rd USENIX Workshop on Hot Topics in Cloud Computing, HotCloud 2011, Portland Oregon.

Torii, S., Yaguchi, E. Ozaki, K, Jindoh, T, Owada, M, & Naitoh, G. (1986). Electronically controlled torque split system, for 4WD vehicles. *SAE Transactions*, *95*(5), 209–216.

Xia, Y., Mitchell, K., Ek, M., Sheffield, J., Cosgrove, B., Wood, E., Luo, L., Alonge, C., Wei, H., Meng, J., Livneh, B., Lettenmaier, D., Koren, V., Duan, Q., Mo, K., Fan, Y., & Mocko, D. (2012). Continental-scale water and energy flux analysis and validation for the North American land data assimilation system project phase 2 (NLDAS-2): 1. Intercomparison and application of model products. *Journal of Geophysical Research: Atmospheres*, *117*(D3). https://doi.org/10.1029/2011JD016048

Zomotor, A., Leiber, H., Neundorf, S., Richter, K. H., & Buechle, K. H. (1986). Mercedes-Benz 4matic, an electronically controlled four-wheel drive system for improved active safety. *SAE Transactions*, *95*(5), 295–304.

APPENDICES

Appendix A. Leveraging Connected Vehicles to Provide Enhanced Roadway Condition Information

Appendix B. Using Probe Data Analytics for Assessing Freeway Speed Reductions During Rain Events

Appendix C. Evaluation of the High-Resolution Rapid Refresh Model for Forecasting Roadway Surface Temperatures

Appendix D. Dashboards for Real-Time Monitoring of Winter Operations Activities and After-Action Assessment

Appendix E. Using Crowdsourced Vehicle Braking Data to Identify Roadway Hazards

APPENDIX A. LEVERAGING CONNECTED VEHICLES TO PROVIDE ENHANCED ROADWAY CONDITION INFORMATION

Abstract

Real-time performance measures are important for agencies to maintain their roadways during the winter season. Sensing systems such as traffic cameras, weather radar, stationary Road Weather Information Systems (RWIS), pavement sensors, mobile weather-sensing units (MARWIS), point speed sensors, and third-party speed data have enabled operators to make tactical data-driven decisions during inclement weather events. However, infrastructure can be expensive to deploy and maintain and may be sparse in rural areas, while speed data alone may not provide enough fidelity in borderline conditions.

This study looks at high-frequency brake pressure, anti-lock brake (ABS) activation, wheel tick, traction-control intervention, hazard lights, and windshield wiper data from the in-vehicle bus to detect changes in the vehicle and driver behavior during changing winter road conditions. The data is reported to the cloud via cellular communication and is viewable in real-time using a map-based web dashboard. Three winter weather events are assessed using in-vehicle data collected from the February–March 2018 period. MARWIS data and a user-based qualitative rating are also used to ground-truth road friction and perceived conditions. Data from hazard lights and wipers indicate early perceived weather and traffic hazards, while ABS and traction control only indicate severe cases of loss-of-friction.

Using 2-sample Kolmogorov-Smirnov test, we found high significance in the reductions of applied brake pressures and rates of braking in winter versus fair weather conditions before vehicle intervention is necessary. As road conditions deteriorate, a driver may reduce braking pressure by up to 60% during typical braking operations, while the rate of braking also is reduced by about 75%. Using the Brown-Forsythe test, the variance of the rate of braking is also found to exhibit statistically significant changes as road friction conditions deteriorate. The greatest increase in brake rate variance is found to occur within the 20–39 mph range at 110 Bar/sec2 and correlates to changes in friction.

The paper concludes that pairwise comparison of driver brake pressure may be a valuable data source indicative of deteriorating road conditions before more severe indicators such as traction control, anti-lock brake, and/or hazard indicators are activated.

APPENDIX B. USING PROBE DATA ANALYTICS FOR ASSESSING FREEWAY SPEED REDUCTIONS DURING RAIN EVENTS

Abstract

Rain impacts roadways such as wet pavement, standing water, decreased visibility, and wind gusts and can lead to hazardous driving conditions. This study investigates the use of high-fidelity Doppler data at 1 km spatial and 2-minute temporal resolution in combination with commercial probe speed data on freeways.

Segment-based space-mean speeds were used and drops in speeds during rainfall events of 5.5 mm/hour or greater over a one-month period on a section of four to six-lane interstate were assessed. Speed reductions were evaluated as a time series over a 1-hour window with the rain data. Three interpolation methods for estimating rainfall rates were tested and seven metrics were developed for the analysis. The study found sharp drops in speed of more than 40 mph occurred at estimated rainfall rates of 30 mm/hour or greater, but the drops did not become more severe beyond this threshold. The average time of first detected rainfall to impacting speeds was 17 minutes.

The bilinear method detected the greatest number of events during the 1-month period, with the most conservative rate of predicted rainfall. The range of rainfall intensities were estimated between 7.5 to 106 mm/hour for the 39 events. This range was much greater than the heavy rainfall categorization at 16 mm/hour in previous studies reported in the literature. The bilinear interpolation method for Doppler data is recommended because it detected the greatest number of events and had the longest rain duration and lowest estimated maximum rainfall out of three methods tested, suggesting the method balanced awareness of the weather conditions around the roadway with isolated, localized rain intensities.

APPENDIX C. EVALUATION OF THE HIGH-RESOLUTION RAPID REFRESH MODEL FOR FORECASTING ROADWAY SURFACE TEMPERATURES

Downing, W. L., Li, H., Desai, J., Liu, M., Bullock, D. M., & Baldwin, M. E. (2020). *Evaluation of the high-resolution rapid refresh model for forecasting roadway surface temperatures* [Paper presentation]. 100th American Meteorological Society Annual Meeting, Boston, MA.

Abstract

Pavement surface temperatures are an important component to winter weather operations and are an important indicator of whether or not to treat the roadways with brine or chemicals to prevent icy conditions. According to FHWA, states and local agencies spend more than $2.3B on winter weather operations per year. Having accurate weather forecasts are essential for making the right call on a winter storm. This study seeks to test the use of an off-the-shelf weather model, the High-Resolution Rapid Refresh (HRRR) model to determine pavement surface temperatures compared with Road Weather Information System (RWIS.) Six locations are used for ground truth in this study.

Residuals between the RWIS and HRRR are compared at each location in addition to the Mean Absolute Error (MAE) for three storms between December 2018 through March 2019. The data are filtered using a solar radiation threshold and precipitation for each forecast hour up to 18 hours in advance of an event. Forecasts with narrow time windows and with solar radiation above 170 W/m2 resulted in the highest errors, while forecasts that predicted precipitation result in the lowest errors. There is an opportunity to leverage emerging connected vehicle temperature and telematics data to ground truth at scale and improve winter forecast predictions in the future.

APPENDIX D. DASHBOARDS FOR REAL-TIME MONITORING OF WINTER OPERATIONS ACTIVITIES AND AFTER-ACTION ASSESSMENT

Abstract

The Indiana Department of Transportation (INDOT) operates a fleet of nearly 1,100 snowplows and spends up to $60M annually on snow removal and de-icing as part of their winter operation maintenance activities. Systematically allocating resources and optimizing material application rates can potentially save revenue that can be reallocated for other roadway maintenance operations. Modern snowplows are beginning to be equipped with a variety of Mobile Road Weather Information Sensors (MARWIS) which can provide a host of analytical data characterizing on-the-ground conditions during periods of wintry precipitation. Traffic speeds fused with road conditions and precipitation data from weather stations provide a uniquely detailed look at the progression of a winter event and the performance of the fleet. This research uses a combination of traffic speeds, MARWIS and North American Land Data Assimilation System (NLDAS) data to develop real-time dashboards characterizing the impact of precipitation and pavement surface temperature on mobility. Twenty heavy snow events were identified for the state of Indiana from November 2018 through April 2019. Two particular instances, that impacted 182 miles and 231 miles of interstate at their peaks occurred in January and March, respectively, and were used as a case study for this paper. The dashboards proposed in this paper may prove to be particularly useful for agencies in tracking fleet activity through a winter storm, helping in resource allocation and scheduling and forecasting resource needs.

APPENDIX E. USING CROWDSOURCED VEHICLE BRAKING DATA TO IDENTIFY ROADWAY HAZARDS

Abstract

Modern vehicles know more about the road conditions than transportation agencies. Enhanced vehicle data that provides information on "close calls" such as hard braking events or road conditions during winter such as wheel slips and traction control will be critical for improving safety and traffic operations. This research applied conflict analyses techniques to process approximately 1.5 million hard braking events that occurred in the state of Indiana over a period of one week in August 2019. The study looked at work zones, signalized intersections, interchanges and entry/exit ramps. Qualitative spatial frequency analysis of hard-braking events on the interstate demonstrated the ability to quickly identify temporary and long-term construction zones that warrant further investigation to improve geometry and advance warning signs. The study concludes by recommending the frequency of hard-braking events across different interstate routes to identify roadway locations that have abnormally high numbers of "close calls" for further engineering assessment.

About the Joint Transportation Research Program (JTRP)

On March 11, 1937, the Indiana Legislature passed an act which authorized the Indiana State Highway Commission to cooperate with and assist Purdue University in developing the best methods of improving and maintaining the highways of the state and the respective counties thereof. That collaborative effort was called the Joint Highway Research Project (JHRP). In 1997 the collaborative venture was renamed as the Joint Transportation Research Program (JTRP) to reflect the state and national efforts to integrate the management and operation of various transportation modes.

The first studies of JHRP were concerned with Test Road No. 1—evaluation of the weathering characteristics of stabilized materials. After World War II, the JHRP program grew substantially and was regularly producing technical reports. Over 1,600 technical reports are now available, published as part of the JHRP and subsequently JTRP collaborative venture between Purdue University and what is now the Indiana Department of Transportation.

Free online access to all reports is provided through a unique collaboration between JTRP and Purdue Libraries. These are available at http://docs.lib.purdue.edu/jtrp.

Further information about JTRP and its current research program is available at http://www.purdue.edu/jtrp.

About This Report

An open access version of this publication is available online. See the URL in the citation below.

Li, H., Saldivar-Carranza, E., Mathew, J. K., Kim, W., Desai, J., Wells, T., & Bullock, D. M. (2020). *Extraction of vehicle CAN bus data for roadway condition monitoring* (Joint Transportation Research Program Publication No. FHWA/IN/JTRP-2020/20). West Lafayette, IN: Purdue University. https://doi.org/10.5703/1288284317212