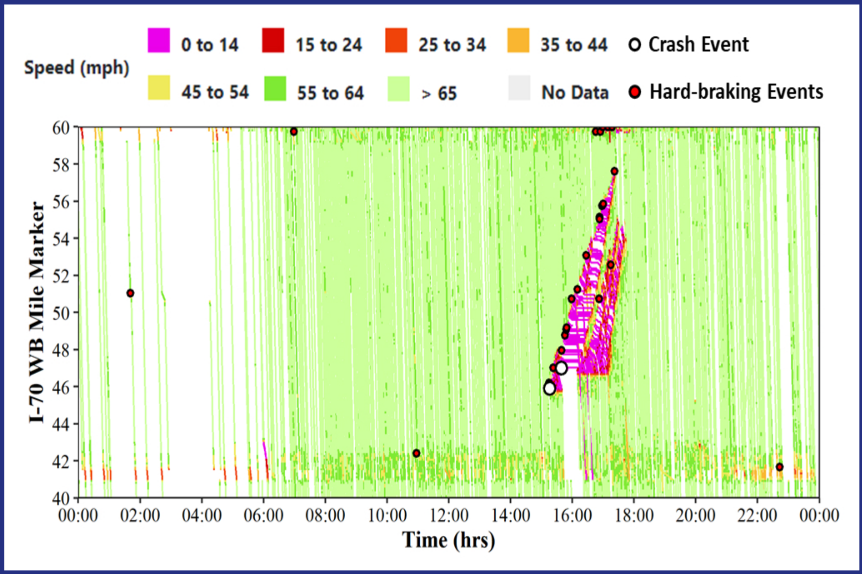
JOINT TRANSPORTATION RESEARCH PROGRAM

INDIANA DEPARTMENT OF TRANSPORTATION
AND PURDUE UNIVERSITY

Integration of Probe Data Tools into TMC Operations



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JOINT TRANSPORTATION RESEARCH PROGRAM

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NOTICE

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16. Abstract
With the advent of probe data, there is a need to virtualize many of the Traffic Management Center (TMC) tools used for analyzing work zones, severe crashes, winter operations, moving maintenance operations, and providing dashboards characterizing overall system mobility. Traditional tools have evolved over the past several years and it is important to develop training materials and make them more accessible to a broad range of Indiana Department of Transportation (INDOT) users and other stakeholders. Over the past several years, agencies have used probe data, mainly 1-minute aggregated segment-based probe data to assess and manage roadways. This study extended traditional segment-based probe data concepts to include enhanced trajectory-based connected vehicle (CV) data, which provides anonymous individual vehicle waypoints at a reporting interval of 3 seconds within a 1.5-meter fidelity radius. The study discusses some of the near-term opportunities, nationwide scalability, and some of the limitations of trajectory data for managing roadways and infrastructure assessment. The tools developed in this study will assist INDOT and other stakeholders in visualizing interstate queues, identifying back-of-queue hard braking events and crashes, identifying alternate diversions during incidents and road closures, enhancing agile management of work zones, estimating traffic signal performance measures without infrastructure investment, and understanding the impact of construction diversions on traffic signals performance.

17. Key Words
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EXECUTIVE SUMMARY

Motivation

With the advent of probe data, there is a need to virtualize many of the Traffic Management Center (TMC) tools used to move maintenance operations; provide dashboards that characterize overall system mobility; and analyze work zones, severe crashes, and winter operations. Traditional tools have evolved over the past several years and it is important to develop training material for adopting into agency business practices and to make the tools more accessible to a broad range of Indiana Department of Transportation (INDOT) users, Indiana State Police (ISP) users and other stakeholders.

Study

Over the past several years, agencies have used probe data—mainly 1-minute aggregated segment-based probe data—to assess and manage roadways. This study extended traditional segment-based probe data concepts to include enhanced trajectory-based connected vehicle (CV) data, which provides anonymous individual vehicle waypoints at a reporting interval of 3 seconds within a 1.5-meter fidelity radius. This study discusses some of the near-term opportunities, the nationwide scalability, and some of the limitations of trajectory data for managing roadways and infrastructure assessment. The chapters in this report enumerate some of the significant tools that have been made accessible to INDOT and other stakeholders.

Results

The tools developed in this study will assist INDOT and other stakeholders with the following.

- Visualizing interstate queues.
- Identifying back-of-queue hard braking events and crashes.
- Identifying alternate diversions during incidents and road closures.
- Agile management of work zones.
- Estimating traffic signal performance measures without infrastructure investment.
- Understanding impact of construction diversions on traffic signals performance.

Workshops, webinars, trainings, and multi-monitor displays installed at INDOT district offices and facilities streamline operations so TMC operators can rapidly identify relevant intelligent transportation systems (ITS) cameras corresponding to an incident and then track the development and recovery of that incident.

The work zone and hard braking reports disseminated weekly provide practitioners and state agencies with the ability to pinpoint hotspots of potential conflict in near real-time, thus providing an opportunity to implement corrective measures to aid the safe flow of traffic.

Lastly, Indiana's work with crowd sourced data has also been recognized by the Federal Highway Administration (FHWA) Every Day Counts (FHWA, 2021a, 2021b) where these tools and dashboards improve real-time operational decision-making and support training and after-action reviews.

Recommendations

The main recommendations from this study include but are not limited to the following.

- Continue webinar dissemination and district engagement on a quarterly basis.
- Continue support of tools (Table 3.1, Figure 6.2, Table 6.1, Figure 7.1, Figure 7.4).
- Transition from segment-based data purchases to trajectory data (Figure 2.5), since it provides higher precision data on agency networks with little to no traditional ITS infrastructure.

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LIST OF ACRONYMS

AOG	Arrival on Green
CV	Connected Vehicle
DSB	Downstream Blockage
FHWA	Federal Highway Administration
GPS	Global Positioning System
INDOT	Indiana Department of Transportation
ISP	Indiana State Police
ITS	Intelligent Transportation Systems
LOS	Level of Service
OEM	Original Equipment Manufacturer
PPD	Purdue Probe Diagram
RDBMS	Relational Database Management System
SF	Split Failure
SQL	Structured Query Language
TMC	Traffic Management Center

1. PROJECT OVERVIEW

1.1 Introduction

Over the past several years a variety of segment-based probe data tools have been developed and routinely used by Purdue and variety of INDOT/ISP users for analyzing work zones, severe crashes, winter operations, moving maintenance operations, and overall system mobility. The current frontier of opportunity is to move from segment-based reporting to individual trajectories reporting at a resolution of 1–3 seconds. Commercial data providers are beginning to enhance trajectory data further by providing event data such as hard braking and hard acceleration. This report discusses some of the near-term opportunities and limitations of this trajectory-based CV data, comparison with traditional segment-based CV data, and the new tools/dashboards developed using this big data to make design, operation, maintenance, and investment decisions to improve the overall system performance.

1.2 Dissemination of Research Results

Several dozen webinars were held over the course of this project to facilitate agile dissemination of results. Some of the major ones are shown in Table 1.1.

In addition, the following is a list of papers that were prepared in part during this project.

- Mathew, J. K., Desai, J. C., Sakhare, R. S., Kim, W., Li, H., & Bullock, D. M. (2021, February). Big data applications for managing roadways. *Institute of Transportation Engineers Journal*, *91*(2), 28–35. https://www.proquest.com/scholarly-journals/big-data-applications-managing-roadways/docview/2486868581/se-2?accountid=13360
- Hunter, M., Mathew, J. K., Li, H., & Bullock, D. M. (2021). Estimation of connected vehicle penetration on US roads in Indiana, Ohio, and Pennsylvania. *Journal of Transportation Technologies*, *11*(04), 597–610. https://doi.org/10.4236/jtts.2021.114037
- Desai, J., Saldivar-Carranza, E. D., Mathew J. K., Li, H., Platte, T., & Bullock, D. M. (2021). Methodology for applying connected vehicle data to evaluate impact of interstate construction work zone diversions. *2021 IEEE Intelligent Transportation Systems Conference (ITSC)*, pp. 4035–4042. https://doi.org/10.1109/ITSC48978.2021.9564873
- Desai, J., Rogers, S., Kim, W., Li, H., Horton, D., Poturalski, J., & Bullock, D. M. (2021). Agile work zone management based on connected vehicle data. *2021 IEEE Intelligent Transportation Systems Conference (ITSC)*, pp. 4051–4056. https://doi.org/10.1109/ITSC48978.2021.9565039
- Saldivar-Carranza, E. D., Kim, W., Scholer, B., Li, H., & Bullock, D. M. (2021, December 7–10). *Scalable cloud-based vehicle trajectory traffic signal performance measures* [Conference session]. ITS America 2021 Annual Meeting, Charlotte, North Carolina.
- Saldivar-Carranza, E. D., Hunter, M., Li, H., Mathew, J., & Bullock, D. M. (2021). Longitudinal performance assessment of traffic signal system impacted by long-term interstate construction diversion using connected vehicle data. *Journal of Transportation Technologies*, *11*(4), 644–659. https://doi.org/10.4236/jtts.2021.114040
- Mathew, J. K., Li, H., Blackwell, M., & Bullock, D. M. (2020, December 10). *Hard-braking event dataset for interstate routes in Indiana*. Purdue University Research Repository. https://doi.org/10.4231/GK80-XG71

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 some of the key findings during this research.

TABLE 1.1
Major webinars to disseminate results

Date	Facility	Purpose
April 26, 2021	Webinar	Presented webinar "Protect the Queue" conducted by R&D for INDOT staff.
May 10, 2021	Webinar	Presented webinar "INDOT Dashboards" conducted by R&D for INDOT staff.
Jun 29, 2021	Webinar	INDOT virtual town hall "Crowdsourced Connected Vehicle Data for Work Zone Performance Monitoring and Management."
Aug 20, 2021	Purdue University	Campus visit by INDOT Executive Staff. Interactive dashboard demos on heatmaps, trajectories, winter operations and traffic signal analytics.

2. CONNECTED VEHICLE TRAJECTORY DATA AND EARLY USE CASES

2.1 Connected Vehicle Data

Nationally, it is estimated that 1 in every 28 vehicles in the United States provides some type of telematics based connected vehicle data through one of the commercial probe data providers (wejo, 2020), although this is anticipated to grow significantly as more than 470 million connected vehicles are expected worldwide by 2025 (ITSdigest, 2018). Two different CV datasets are now available.

2.1.1 Trajectory Data

The CV trajectory data consists of individual vehicle waypoints with a reporting interval of 3 seconds and a 1.5-meter fidelity radius. Every waypoint has the following information attached: GPS location, timestamp, speed, heading, and an anonymized unique trajectory identifier. By linking individual waypoints using their trajectory identification number, a vehicle's trajectory can be obtained.

2.1.2 Event Data

The CV event data consists of discrete events such as hard braking, hard acceleration and seatbelt status each of which has the following information: GPS location, timestamp, and speed. A hard braking (or acceleration) event is defined as a deceleration (or acceleration) greater than 8.76 ft/s^2 (or 2.67 m/s^2 which is defined by the data supplier).

Figure 2.1 shows the number of CV events accessible during August 2020 from 11 states in USA from one connected vehicle data provider. In total, more than 167 billion anonymized movement data was recorded during this period. In addition, more than 103 million hard braking events occurred during this period for those same states. Figure 2.2 illustrates over 10 billion connected vehicle trajectory records and nearly 25 million event records generated per month between the months of April and August 2021 for Indiana. On a national level, over 400 billion connected vehicle events are now available every month (Downing, 2020). As additional data providers and original equipment manufacturers (OEMs) enter this data space, the volume of this connected vehicle data is expected to dramatically increase.

2.2 Network Level Summary Data

One of the primary objectives of the traffic incident management performance measurement program developed by FHWA is to reduce the number of secondary crashes (FHWA, 2020b). Past studies have shown that crash rates during congested periods can increase by a factor of 24 compared to uncongested periods on interstates (Mekker et al., 2020). Hard braking events, which are "near-misses" or "close calls" during these periods are potential predictors of future crash events. Although only a few studies have analyzed hard braking events and crash frequencies (Bagdadi, 2013; Bagdadi & Várhelyi, 2013), one recent study found that there was approximately 1 crash per mile for every 147 hard braking events at 4.7% penetration within the vicinity of an interstate work zone (Figure 2.3) (Desai et al., 2021).

Indiana has developed several web-based dashboards using the CV data to monitor interstate conditions in real-time, especially during construction, interstate crashes, traffic detours and winter operations (Desai et al., 2020; Kim et al., 2020; Mcnamara, 2015). Figure 2.5a is adapted from a similar dashboard Indiana uses to monitor statewide interstate queues and hard braking events. On a typical day, Indiana has approximately

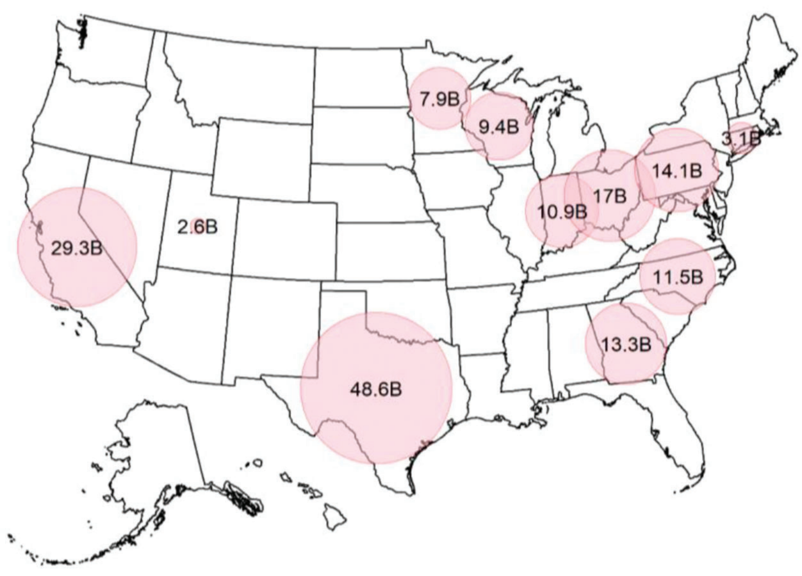
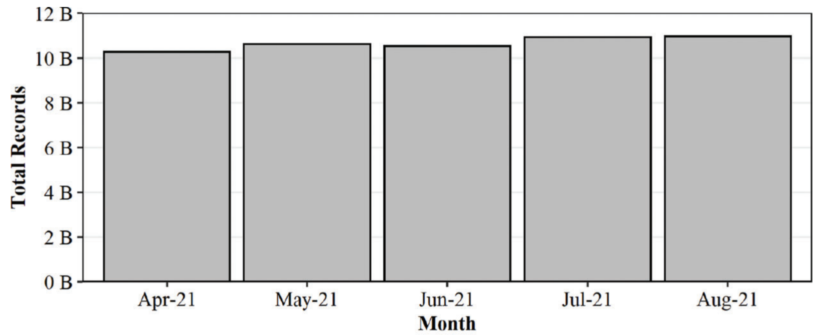
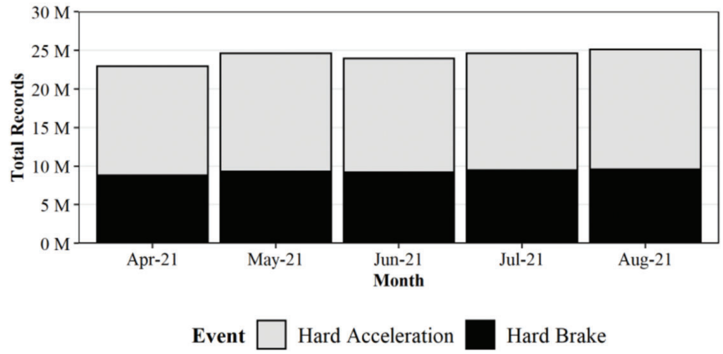


Figure 2.1 Over 167 billion connected vehicle records across 11 states, in August of 2020.



(a) More than 10 billion trajectory records per month



(b) Nearly 25 million event records per month

Figure 2.2 Connected vehicle records for Indiana between April and August of 2021.

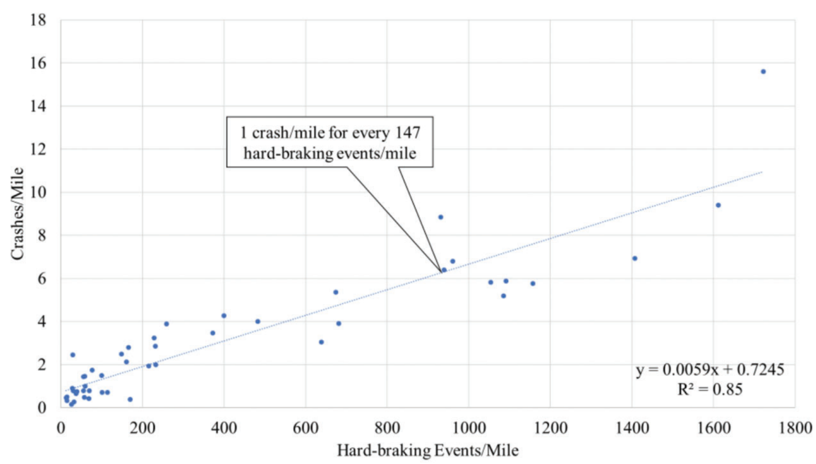


Figure 2.3 Scatter plot with a linear trendline showing crashes and hard-braking events per mile across 23 interstate work zones in Indiana from July 1–August 31, 2019.

397 mile-hours of traffic operation below 45 mph on interstates (12% of the state's interstate roadway system) and 220,000 hard braking events. Daily average mile-hours of congestion per week, for a nearly 3-year period on Indiana's interstates categorized by INDOT District is shown for reference in Figure 2.4.

2.3 Trajectory Data

Figure 2.5a illustrates a case study showing a time-space diagram of individual trajectories color coded by speed overlaid with hard braking events (red dots) for I-70 in the westbound direction between mile markers 40 and 60 on September 24, 2020. Approximately 536,000 data points from nearly 2,200 connected vehicles were linear referenced to this route after performing geo-spatial analysis on more than 365 million records. The pink hues signify data points with speeds below 15 mph (24 kph). Crash data obtained from the state repository shows a primary crash (callout P) and a secondary back-of-queue crash (callout S) that occurred around 15:00 hours.

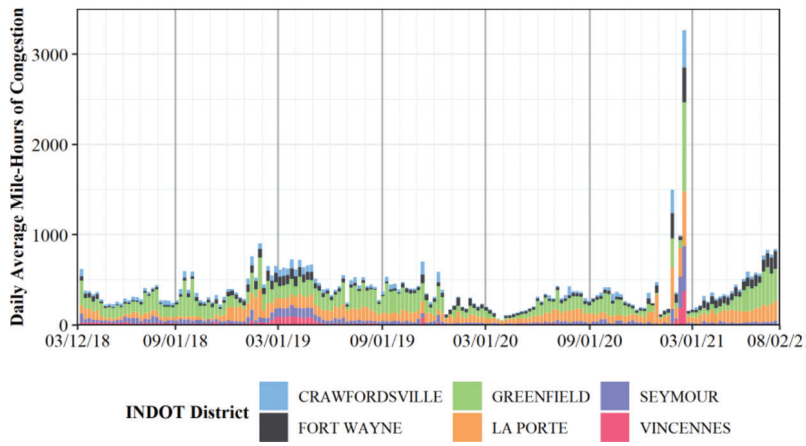


Figure 2.4 Daily average of weekly mile-hours of congestion for Indiana interstates categorized by the INDOT District (March 12, 2018–August 8, 2021).

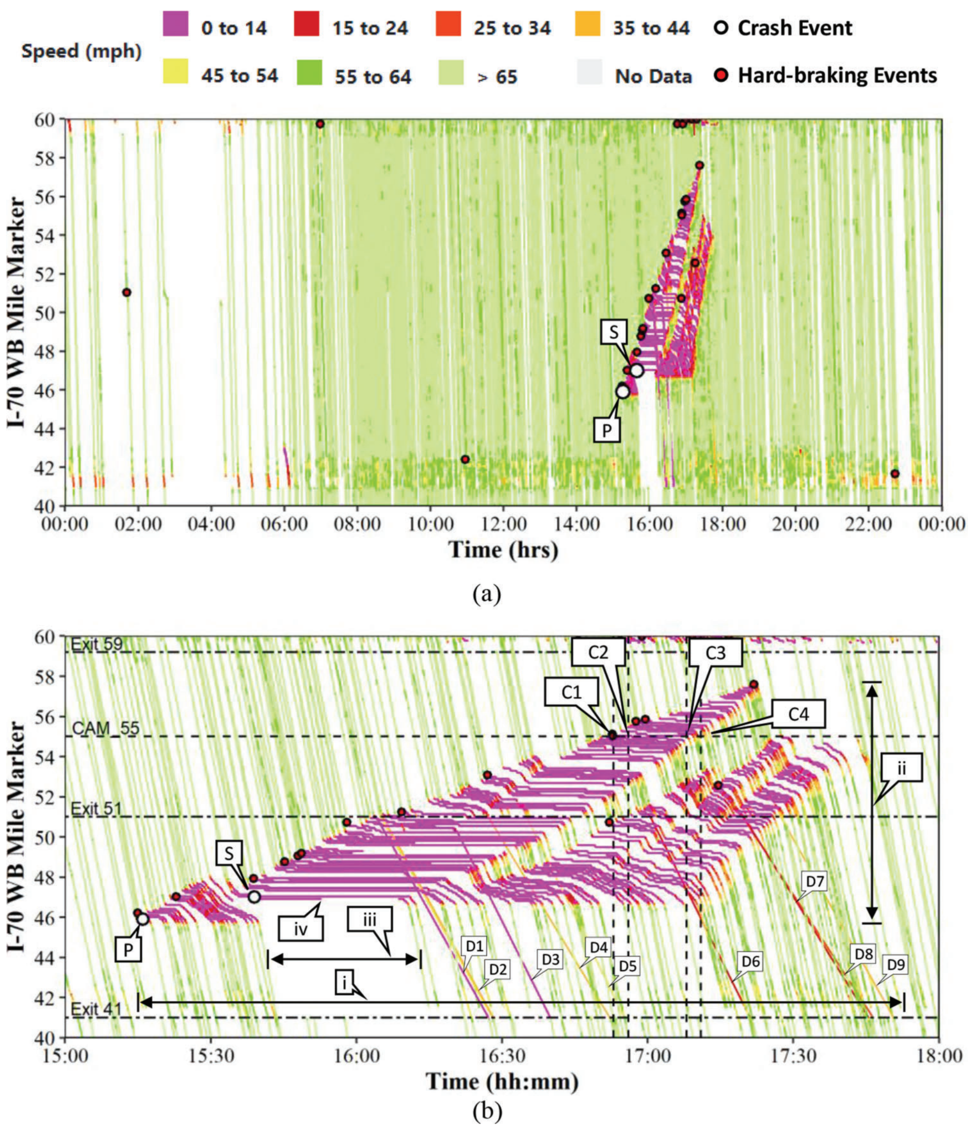
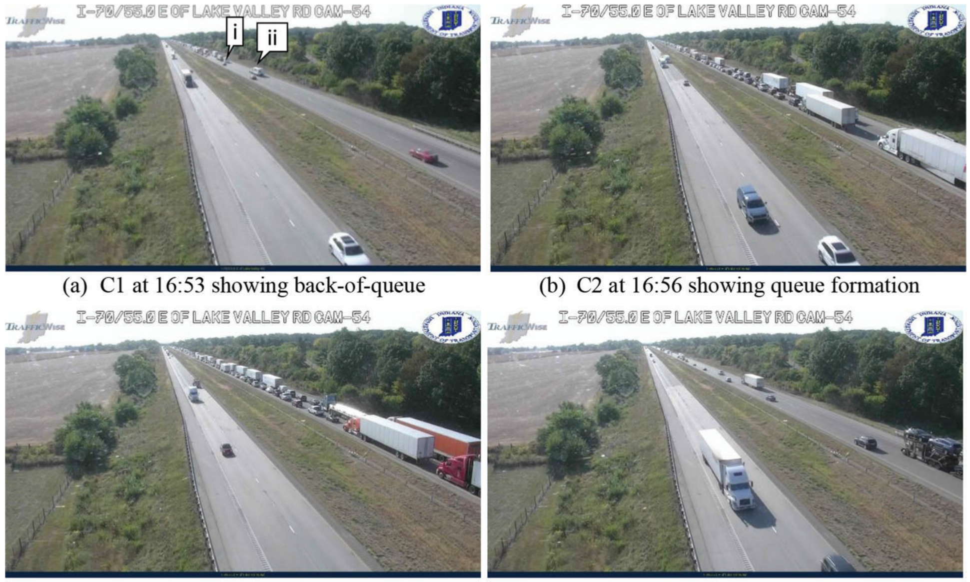


Figure 2.5 September 24, 2020, traffic heatmap for Indiana I-70 overlaid with trajectories colored by speed, crash events, and hard braking events: (a) 24-hour view and (b) detailed view between 15:00 and 18:00.



(a) C1 at 16:53 showing back-of-queue

(b) C2 at 16:56 showing queue formation

(c) C3 at 17:08 when queue begins to dissipate

(d) C4 at 17:11 showing free-flow conditions

Figure 2.6 Camera images from callouts C1 to C4 on Figure 2.5 showing queue formation and queue dissipation on I-70 WB.

Figure 2.5b illustrates the detailed assessment of the queuing during the event that occurred between 15:00 and 18:00 hours. The two crashes resulted in a 12-mile (19.3 km) long queue (callout ii) that impacted traffic for nearly 2.5 hours (callout i). The interstate was also closed for more than 30 minutes (callout iii) after the secondary crash. Several hard braking events (red dots) occurring at the boundary between the congested and uncongested regime indicate the critical areas where drivers decelerate to avoid back-of-queue or rear-end collisions. This hard braking information and locations will be helpful for agencies to strategically provide advance warnings and other queue mitigation solutions to improve the situational awareness of nearby motorists.

Another feature of this enhanced probe data is the additional information that agencies can gather from this dataset. Callout iv shows a vehicle turning off ignition when the interstate was closed, and later resuming the trip after the interstate was opened to traffic. Such rare events on interstates are potential indicators of traffic shutdowns. Callouts D1 to D9 shows the diverting trips that avoid the queues by taking Exit 51 before returning to the interstate at Exit 41. This information helps agencies understand the impact of diversion routes.

2.4 Independent Validation of Queues Identified by Connected Vehicle Data

Indiana has approximately 350 ITS cameras in its the statewide surveillance system. These cameras can be used to validate and illustrate the value of CV data. The location of the slowdowns depicted in the CV heatmap (Figure 2.5) can be associated with fixed ITS cameras and integrated into a statewide surveillance tool. Callouts C1 to C4 on Figure 2.5b corresponds to the images captured by the ITS camera (Figure 2.6) near MM 55. The back-of-queue (Figure 2.6, callout i) and vehicle braking at back-of-queues around 16:53 (Figure 2.6, callout ii) are clearly evident. Figure 2.6b shows the long queues formed within 3 minutes of Figure 2.6a. The queue dissipation begins around 17:08 (Figure 2.6c) and clears around 17:11 (Figure 2.6d). The images captured by the cameras independently validate the queues identified by the CV data.

3. MARKET PENETRATION

CV data is an important asset for agencies to evaluate the performance of freeways and arterials, provided there is sufficient penetration to provide statistically robust performance measures. A common concern by agencies interested in using crowd sourced probe data is the penetration rate across different types of roads, different hours of the day, and different regions.

A penetration assessment study (Hunter et al., 2021) was conducted across 54 locations between Indiana, Ohio, and Pennsylvania (Figure 3.1) on select Wednesdays and Saturdays between January 2020 and June 2021. Data from permanent and continuous traffic count stations were compared with unique connected vehicle trips in the same region to generate penetration estimates. Analysis on Ohio and Pennsylvania were limited to the two days in August 2020 due to data availability.

The 54 locations analyzed had percent penetration values between 1.8% and 9.8% with an average percent penetration of around 4.4% and a median penetration of 4.5% (Table 3.1, Table 3.2, and Table 3.3).

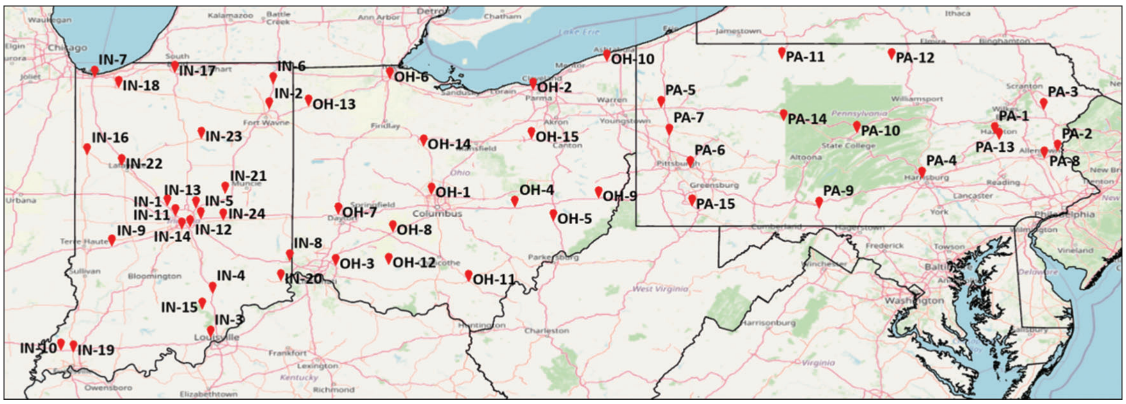


Figure 3.1 Location of DOT count stations.

TABLE 3.1
Average estimated penetration for Indiana

Location	Int/SR	AADT	Jan 2020 (%)	Aug 2020 (%)	Sept 2020 (%)	Dec 2020 (%)	Jan 2021 (%)	May 2021 (%)	June 2021 (%)
IN-1	Int	61,790	4.1	–	–	–	–	–	–
IN-2	Int	56,158	3.8[a]	3.0	3.0	4.1[a]	4.5	2.9	2.7
IN-3	Int	56,431	4.4	–	3.7[a]	3.4	3.5	3.5	3.6
IN-4	Int	34,932	3.9	3.8	3.9	3.5	3.8	4.2	
IN-5	Int	52,737	4.5	3.8[a]	3.8	3.8	3.6	4.1	4.1
IN-6	Int	25,406	–	5.6	5.9	5.2	–	–	–
IN-7	Int	97,824	–	–	4.0	1.8[a]	2.2	–	–
IN-8	Int	31,121	4.3	–	–	–	–	–	–
IN-9	Int	30,506		3.2	3.1	2.7	2.6	3.5	3.6
IN-10	Int	10,794	4.5	–	–	–	–	–	–
IN-11	Int	106,368	–	–	4.4[a]	5.2	5.4	–	–
IN-12	Int	92,540	6.8	–	–	5.9	5.9	–	–
IN-13	Int	114,909	6.3[a]	5.4	5.5	5.2	5.0	5.5[a]	5.6[a]
IN-14	Non-Int	37,738	5.4	5.0	5.1	5.0	5.3	5.4	5.4
IN-15	Non-Int	3,737	5.3	4.5	4.7	–	–	4.6	4.5[a]
IN-16	Non-Int	3,176	3.8	4.7	5.3	3.7	5.4[a]	4.6	4.6
IN-17	Non-Int	35,793	3.1	3.1	3.3	3.0	3.7	3.6	–
IN-18	Non-Int	17,392	4.7	4.8	–	–	–	–	–
IN-19	Non-Int	18,954	4.8	4.4	4.7	4.4	4.3	4.3	4.3
IN-20	Non-Int	10,524	3.6	6.4	4.8	4.7	4.8	5.1	5.2
IN-21	Non-Int	15,529	9.8	–	8.9	–	–	8.4	7.8
IN-22	Non-Int	19,864	4.8	4.5	4.3	4.3	4.1	4.3	4.5
IN-23	Non-Int	9,566	5.7	5.3	5.0	5.3	5.5	5.5	5.6
IN-24	Non-Int	7,058	5.4	5.7	3.6	5.3	5.5	5.7	–

Note: Blank boxes indicate that INDOT counts were unavailable.
[a]Count station data only available for one day of the two days.

TABLE 3.2
Average estimated penetration for Ohio

Location	Int/SR	AADT	Aug 2020 (%)
OH-1	Int	113,510	3.5
OH-2	Int	74,614	5.7
OH-3	Int	76,790	5.0
OH-4	Int	32,039	3.4
OH-5	Int	14,489	4.5
OH-6	Int	58,936	3.3
OH-7	Int	61,639	4.3
OH-8	Int	34,154	3.7
OH-9	Int	31,033	3.9
OH-10	Int	27,706	4.8
OH-11	Non-Int	6,313	4.5
OH-12	Non-Int	7,170	7.8
OH-13	Non-Int	14,363	4.1
OH-14	Non-Int	15,164	4.7
OH-15	Non-Int	15,368	4.3

TABLE 3.3
Average estimated penetration for Pennsylvania

Location	Int/SR	Aug 2020 (%)
PA-1	Int	3.3
PA-2	Int	2.7
PA-3	Int	3.5
PA-4	Int	2.9
PA-5	Int	3.9
PA-6	Int	4.3
PA-7	Int	5.1
PA-8	Int	2.9
PA-9	Int	3.8
PA-10	Int	3.8
PA-11	Non-Int	4.6
PA-12	Non-Int	4.5
PA-13	Non-Int	4.3
PA-14	Non-Int	5.4[a]
PA-15	Non-Int	4.4

[a]Count station data only available for one day of the two days.

Indiana, Ohio, and Pennsylvania had similar monthly percent penetration for August 2020 with average percent penetrations of 4.6%, 4.5%, and 3.9% and median percent penetrations of 4.6%, 4.3%, and 4.0%, respectively.

4. STORAGE AND DATA ANALYTICS PLATFORM

With increasing probe penetration rates and additional vehicle attributes in the data, it has become a challenge for agencies to manage the computing infrastructure necessary to support storage and analytics. For example, one month of connected vehicle data in Indiana is over one terabyte in size, consisting of over 10 billion records. The data must be stored on a platform that enables quick analysis to support interactive dashboard access for agencies managing the roadways. Typically, a relational database management system (RDBMS) is employed for such purposes, such as SQL Server. Traditional server procurement involves specifying how much storage is required, type of storage, processing power, memory, database software licensing and backups. Recent advancements allow storage and database management to be done in the cloud (Google, n.d.b).

While there are no upfront fixed costs for cloud-based systems, the monthly pricing depends on how much data is stored, how long it is stored for, and what analytics are performed against the dataset. There are several major cloud data providers available for an agency to choose from. A representative cloud cost for the Indiana connected vehicle data is $20 per month per terabyte to store the data and $5 to analyze each terabyte (Google, n.d.a). To put it in perspective, running an analysis on a corridor with 100 million GPS points, or about 10 gigabytes, would cost five cents. Depending on the use case and data retention policy, agencies now have several options between cloud platforms and infrastructure maintained on-premise at the agency. In many cases, the data architecture and retention policies will have the most significant impact on cloud computing costs.

5. LIMITATIONS AND OPPORTUNITIES

Over the past several years agencies have used probe data, mainly segment-based probe data to assess and manage roadways. There are several third-party commercial providers that supply 1-minute aggregated speed data from multiple sources including smartphone apps, in-cab navigation systems and telematics over predefined roadway segments. Throughout the entire Indiana interstate highway network, these segments have ranged from 0.003 miles to 0.5 miles (Remias, 2012).

The trajectory-based CV data has several advantages over the traditional segment-based CV data.

1. *High-fidelity:* Trajectory-based CV data reports the waypoints and associated attributes every 3 seconds without any aggregation. The increased fidelity for example allows precise back-of-queue identification, cyclic traffic signal patterns and lane utilization to be analyzed. In future, this could also provide vehicle classification details for additional analysis. Segment-based CV data reports the aggregated data collected from different sources in 1-minute intervals.
2. *Additional enhanced attributes*: Trajectory data can provide additional attributes such as hard acceleration, wind shield wiper use or seat belts on/off for enhanced analysis and decision-making investments. The attributes will keep on growing with evolution of electric and autonomous vehicles such as lane keep assist detection, battery life, electric charging desert zones etc. Segment data due to its innate nature does not provide any other information but traffic speeds.
3. *Real-time raw data without data fusion*: Segment data is opaque on the underlying distribution of individual vehicle dynamics and uses predictive modelling (from historic data) to generate speed estimates during the

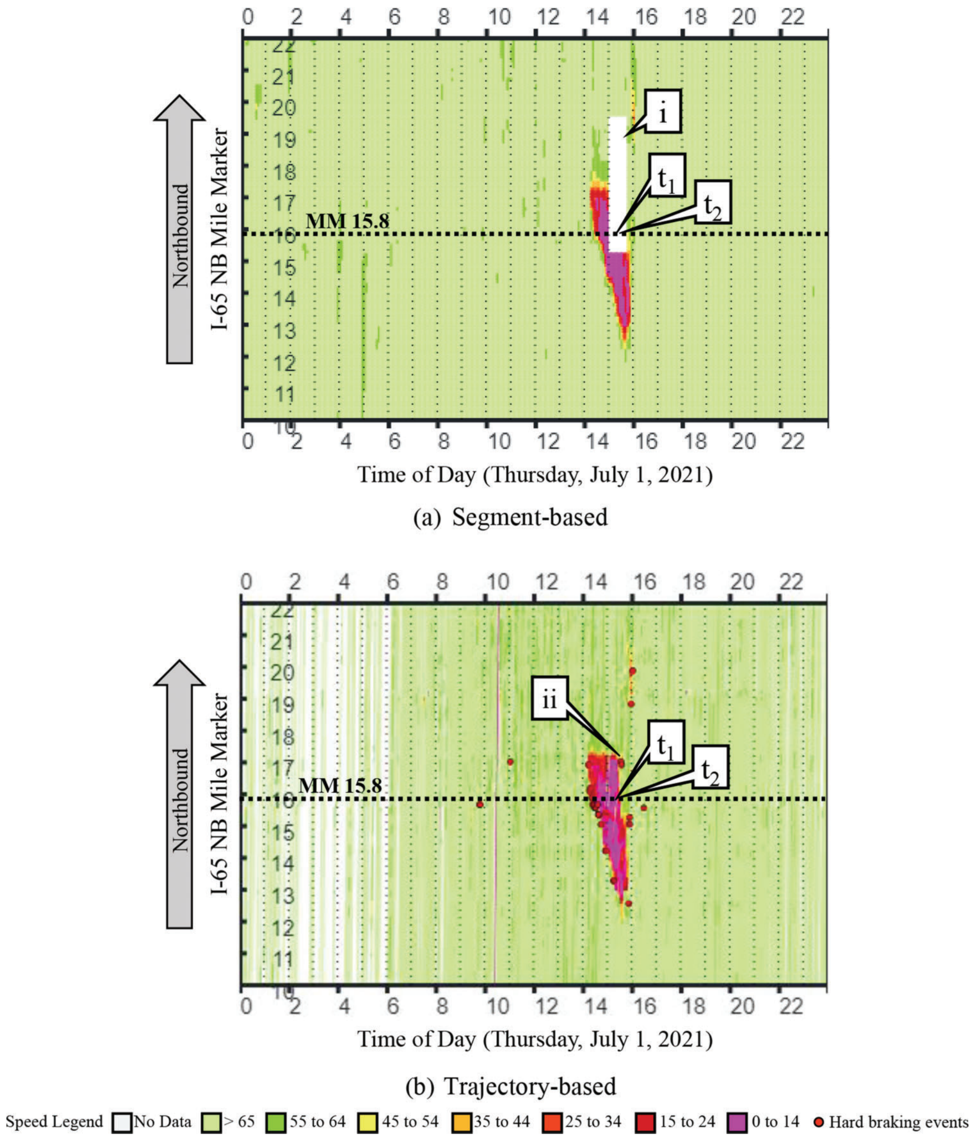


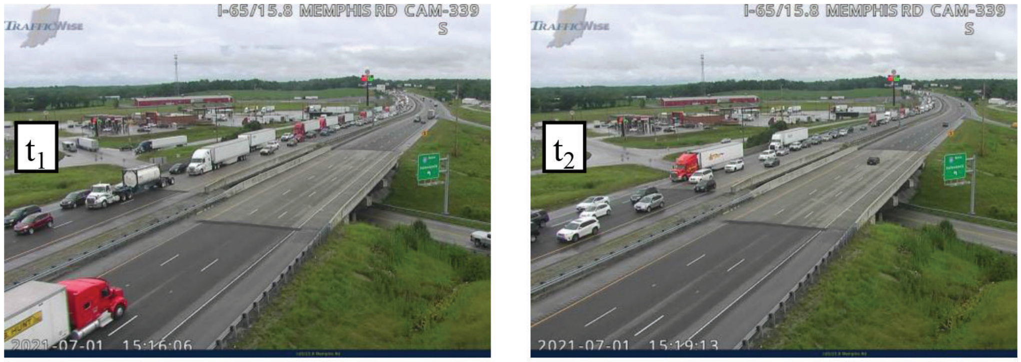
Figure 5.1 Heatmap comparisons along I-65 NB between MM 10 to MM 22 on Thursday, July 1, 2021.

absence of real-time data. On the other hand, trajectory data only provides the raw real-time data without any modelling or predictions, thereby providing more accurate and reliable real-time traffic conditions.

The inherent differences in data collection and reporting could sometimes lead to several discrepancies between the two datasets. Figure 5.1 compares heatmaps generated using segment-based (Figure 5.1a) and trajectory-based (Figure 5.1b) CV data along I-65 NB between MM 10 and MM 22 on Thursday, July 1, 2021. Segment data heatmap suggests that there was interstate closure between 3 PM and 4 PM from MM 15 to MM 19 as shown by callout i. During the similar time period and location, trajectory data shows slow moving vehicles (callout ii) but there was no full closure or closed lanes on the interstate. Trajectory data also provides additional attribute, hard braking events (red dots) overlaid on top of the heatmaps.

Figure 5.2 shows compares images at 3:15 PM (callout t_1) and at 3:18 PM (callout t_2) from an ITS camera around MM 15.8 on I-65. The locations of these images are shown on heatmaps in Figure 5.1 along the black dotted line. Moving traffic was observed with congested conditions from two images that were 3 minutes apart. This serves as a ground-truth validation for the information provided by trajectory data (Figure 5.1b). Another independent source of validation, the INDOT TrafficWise Twitter feed, also reported slow traffic on all lanes (Figure 5.3).

However, one of the near-term limitations of the trajectory data is the market penetration. As seen in Section 3, estimated penetration of CV's range from 1.8% to 9.8% with an average percent penetration of around 4.4%. Since the current data is from connected passenger vehicles, there is a significant outage during early hours, as shown by the white gaps between 01:00–06:00 on Figure 5.1b. Nevertheless, with the



(a) At 3:15 PM (t1)   (b) At 3:18 PM (t2)

Figure 5.2 Camera images along I-65 at MM 15.8 on Thursday, July 1, 2021.


INDOT TrafficWise
@TrafficWise

I-65 MM 13.0 NB near Memphis/mile 13 All lanes slow <= 20 mins due to heavy traffic

3:45 PM · Jul 1, 2021 · Trafficwise

Figure 5.3 Interstate traffic conditions alert shared on Twitter from July 1, 2021 (INDOT TrafficWise, 2021).

addition of more connected cars and truck OEMs, this penetration is likely to grow thereby reducing the data outages.

6. WORK ZONE PERFORMANCE MEASURES

Construction work zones are perhaps the nearest term opportunity for agencies to use connected vehicle data because it provides high-precision data on sections of their networks that are under construction, but with little or no traditional ITS infrastructure. Several performance measures including mile-hours of congestion, number of crashes, and number of hard braking events can be tracked systemwide as well as by districts and interstates. Detailed reports with before-and-after comparisons are also shared with INDOT on a weekly basis (Appendix A. Weekly Work Zone Report and Appendix B. Weekly Interstate Hard Braking Report).

Two near-term applications using the CV data for evaluating the impact of diversions and agile management during construction work zones are detailed in the next sub sections.

6.1 Impact of Interstate Construction Work Zone Diversions

Diversion of Interstate traffic can significantly impact the surrounding road network with increased volumes and congestion. Commercially available connected vehicle data was used to examine the impact of a construction zone on Indiana I-70 with 7 days of reduced interstate capacity that resulted in significant diversion onto US-40, an adjacent signalized arterial east of Indianapolis. Approximately 12 million connected vehicle GPS points, collected at nominal 3 second intervals were analyzed over an eight-week period for an 11-mile section of I-70 and similar length parallel section of US-40 shown in Figure 6.1. Congestion peaked at approximately 5 PM on August 10, 2020 and resulted in a 115% increase in sampled vehicle volumes using the adjacent US-40. Critical intersections along US-40 experienced an increase of approximately 1,175% in split failures. Travel time on the US-40 corridor increased by 16% during the peak hour.

Additionally, CV trajectory data with waypoints available every 3 seconds enabled travel time and diversion rate analysis on I-70, showing a 102% increase in travel times and 3% diversion rate during the week of congestion. Correspondingly, the adjoining US-40 corridor observed a 92% increase in sampled volumes with travel times increasing by as much as 16% during peak congestion on I-70. Analysis of traffic signal operations on the 12-intersection corridor with trajectory-based traffic signal performance measures showed the impact the interstate construction diversions had on the adjoining arterial, namely, an 872% increase in trajectories experiencing split failures, 2% decrease in arrival on green (AOG), 220% increase in trajectories experiencing downstream blockage and a degradation of the corridor level of service (LOS) from A to B.

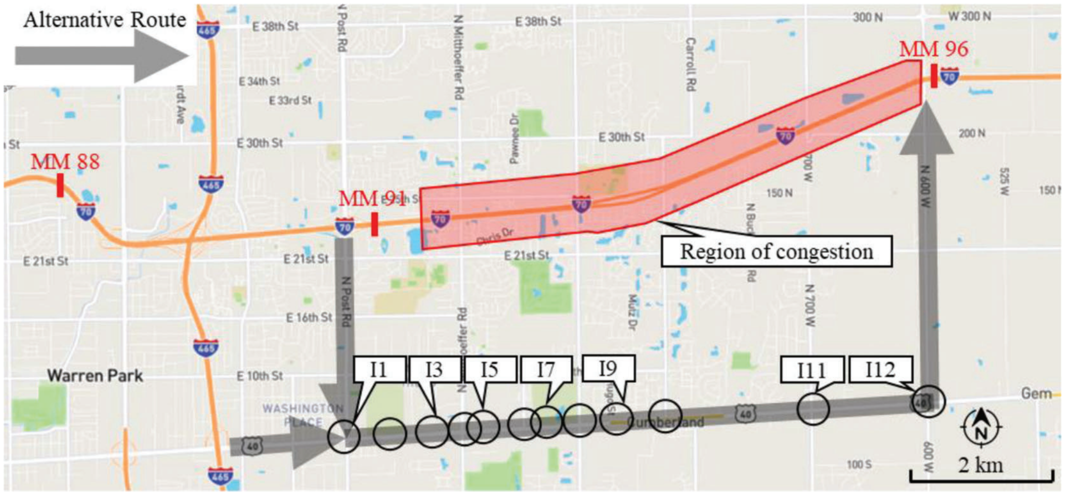


Figure 6.1 Diversion case study location.

A representative visualization is depicted in Figure 6.2 that shows the impact of interstate congestion on the I-70 corridor on trajectory counts as well as stopping trajectories on the adjacent arterial. Figure 6.2a shows a stacked bar representation of the mile-hours of congestion on I-70 EB by hour of day, computed by summing lengths of quarter-mile segments where median speed of trajectory data points over an hour dipped below 45 mph. Correspondingly, Figure 6.2b shows the number of unique trajectories that traversed US-40 from Post Road (I11) to S600W (I12) during the same time period. While the pre-construction period from July 6 to August 8 observed an average of 96 trajectories per weekday on US-40, the period of I-70 congestion from August 10 to 18 showed an average of 182 trajectories per weekday on the same stretch of US-40. This clearly points to diverging trajectories from I-70 resulting in an increase in sampled volumes on US-40. It is visually discernible from Figure 6.2a and b that during the week of congestion, peak mile-hours of congestion observed on I-70 in the evening hours of 3 PM to 7 PM show a corresponding rise and thus a direct impact in sampled vehicle volumes on US-40. When zeroing in on a particular intersection, Figure 6.2c shows the percentage of trajectories, by number of stops, for vehicles traveling EB through at German Church Rd. (I8) for the weekdays between July 6th and August 28th, where the daily increase on split failures due to congestion can be appreciated.

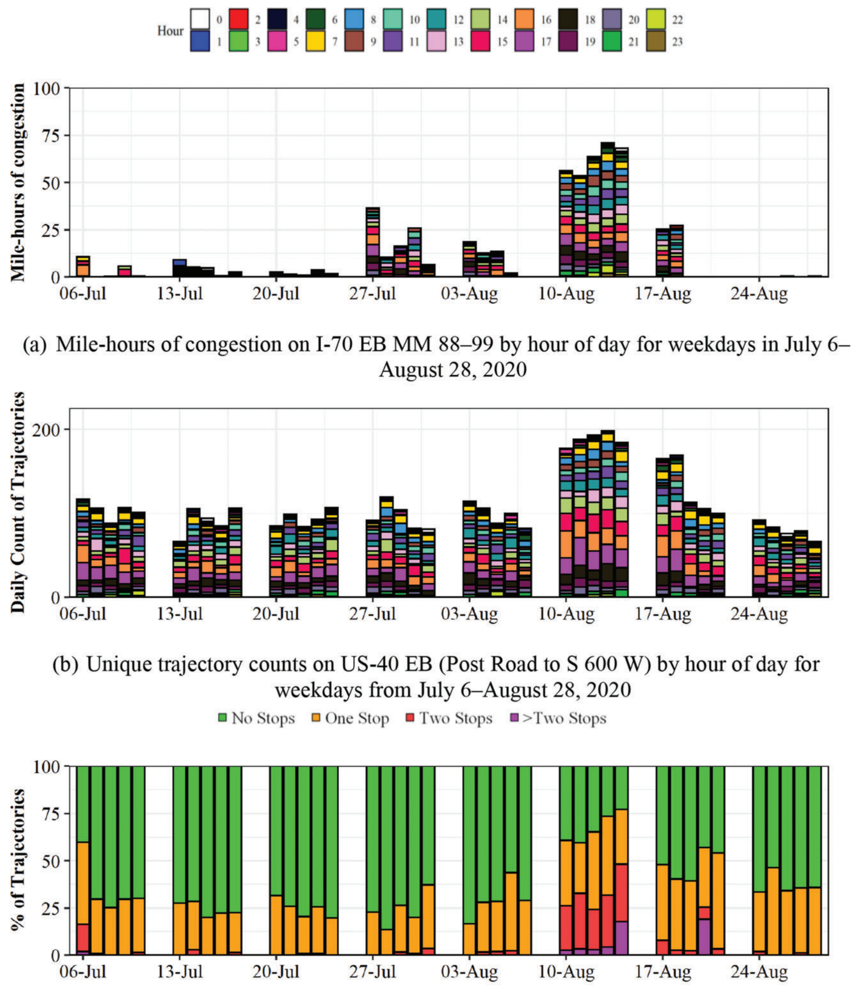
The analysis, methodology, and results obtained herein can potentially assist agencies and contractors when planning future construction activity and recommending alternative routes to the traveling public. With increasing penetration rates and widespread availability, the use of connected vehicle data provides a viable path forward for agencies by removing any spatial constraints that may be imposed by traditional ITS sensors and affords them the freedom to scale these methodologies to any interstate construction project in the United States.

6.2 Agile Work Zone Management

Peak period lane closures can result in significant queueing on major interstates. Many state agencies thus have a lane closure policy in place based upon historical time of day and day of week traffic volumes. The COVID-19 pandemic resulted in a significant reduction in traffic volumes in Indiana during March through May of 2020. In some periods, traffic volume reductions were over 35%. During this period, INDOT implemented an agile lane closure policy based upon observed volumes and monitored those exceptions using connected vehicle data.

This section examines 11 lane closure exceptions on 4 interstates across Indiana. Congestion comparisons were made for each exception for the same time period in 2020 and 2019. Even with the lane closures exceptions, it was found that 10 out of 11 sections had fewer mile-hours of congestion. The total mile-hours of congestion for all 11 sections reduced from 1,281 mile-hours in 2019 to 244 mile-hours in 2020. Overall, crashes decreased from 125 in 2019 to 70 in 2020. Year-over-year comparisons for these exceptions demonstrated significant opportunities for agile work zone lane closure practices when coupled with close monitoring of crash and congestion measures derived from connected vehicle data.

As a result of a statewide stay-at-home order to address COVID-19 initiated in March 2020, traffic on state highways in Indiana saw a 30% to 45% decrease in passenger vehicles in March. When compared to a control week beginning February 22nd, weekly average personal travel nationwide in the US as well as in Indiana was down approximately 30% for 6 weeks starting March 27th, 2020. This reduction in traffic



(a) Mile-hours of congestion on I-70 EB MM 88–99 by hour of day for weekdays in July 6–August 28, 2020

(b) Unique trajectory counts on US-40 EB (Post Road to S 600 W) by hour of day for weekdays from July 6–August 28, 2020

(c) Percentage of trajectories by number of stops for vehicles traveling EB through at German Church Rd (I8 on Figure 5.1)

Figure 6.2 Impact of I-70 congestion on US-40 volumes and number of stops at German Church Rd.

volumes resulted in an opportunity for INDOT to implement agile lane closure exceptions. Crash data and connected vehicle data were used to assess the implementation of these lane closure exceptions and their impact on traffic.

Table 6.1 lists these 11 lane closure exceptions, and columns 2 and 3 identify the route and the mile marker range they were active on. Figure 6.3 shows these lane closure exception locations on a statewide map for geographical context. Congestion trends and crash activity for 11 lane closure exceptions granted by INDOT on 4 interstate roadways were analyzed over a 6-week period in 2020. The same 6-week period from 2019 was analyzed for base level comparison. This study observed an overall 81% decrease in congestion and 44% decrease in crashes in 2020 compared to 2019. Although the traffic volumes changes were unprecedented, these results support the use of agile data-driven tools for agencies to be flexible in their lane closure policies in conjunction with close monitoring of the impact of those exceptions.

While the exceptions analyzed in this study only constituted 139 miles of a total of nearly 2,500 centerline miles of interstate roadways in Indiana, their successful implementation makes a strong case for adopting agile work zone project management practices on a larger scale in conjunction with close monitoring made possible by access to real-time connected vehicle speeds, hard-braking and hard-acceleration data. Exceptions analyzed for this research were the first 11 instances of INDOT utilizing agile lane closure procedures in 2020. Agile lane closure policies were subsequently implemented at an additional 25 locations across the state. In addition to including crash date and time information in the dashboards, INDOT is now incorporating hard-braking events reported by connected vehicles to provide even faster assessment on system operation.

TABLE 6.1
Year-over-year comparison of mile-hours of congestion and crash counts for lane closure exceptions

2020 Exception	Route	Evaluation Area Mile Marker Range	Mile-Hours of Congestion (MHC)		% Change in MHC	Crash Count		% Change in Crashes
			2020	2019		2020	2019	
E1	I-65	MM 205–230	12	179	-94	12	18	-33
E2	I70 W	MM 103–105	1	6	-85	1	1	0
E3	I70 E	MM 95–104	96	26	276	3	8	-63
E4	I65	MM 158–168	8	69	-88	3	14	-79
E5	I65	MM 20–22	1	18	-96	3	0	–
E6	I70	MM 3–7	48	59	-19	6	4	50
E7	I65	MM 147–149	12	23	-48	10	4	150
E8	I65	MM 106–108	7	61	-89	10	17	-41
E9	I70	MM 37–41	21	28	-26	2	2	0
E10	I69	MM 263–271	19	578	-97	7	29	-76
E11	I-265	MM 0–7	19	234	-92	13	28	-54
Total			*244*	*1,281*	*-81*	*70*	*125*	*-44*

Note: Red and green numbers indicate an increase and decrease in metrics, respectively.

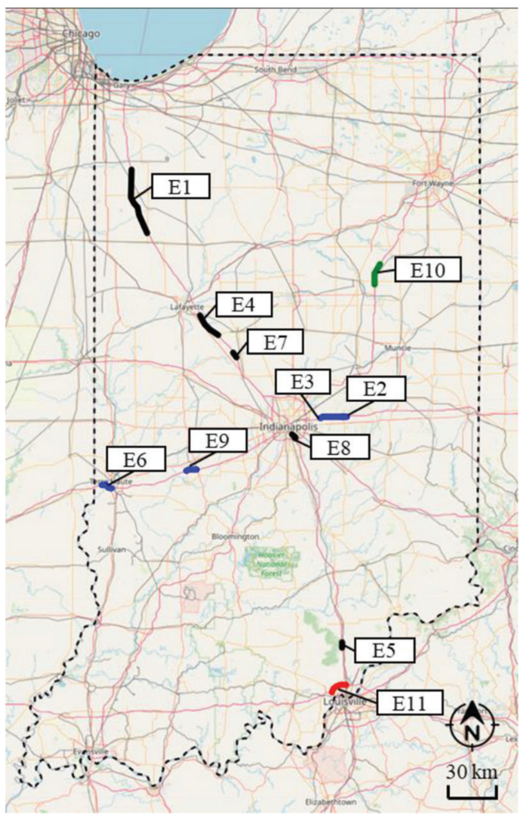


Figure 6.3 Statewide map of 11 lane closure exceptions.

7. TRAFFIC SIGNAL PERFORMANCE MEASURES

7.1 Scalable Cloud-Based Vehicle Trajectory Traffic Signal Performance Measures

Traffic signal performance measures have historically been derived from either vehicle probes or infrastructure-based techniques. With over 400 billion CV trajectory records generated per month in just the continental United States, it is important to develop efficient cloud-based processing methods and accompanying visualization tools for agencies to efficiently use this new data source.

The objective of this study was to leverage real-time CV data streams and cloud technologies to cost-effectively transform billions of CV trajectory waypoints into the following traffic signal performance measures.

- Arrivals on green (AOG)
- Split failures (SF)
- Downstream blockage (DSB)
- Level of service (LOS) based upon average control delay (TRB, 2010)

A web dashboard is developed as a user interactive tool that gets input for start and end date period, selections of location, type of movement and direction of traffic along the corridor, and type of performance measure to analyze. The tool has proven to be especially effective when comparing traffic signal performance throughout corridors and time.

A case study on Indiana State Route 37 compares pre-COVID-19 (January 2020) traffic signal performance measures with operations during COVID-19 restrictions (June 2020) (Figure 7.1). The case study highlights how the performance graphics can provide agencies with a quick and robust way to identify poorly performing intersection movements by time of day and/or locate where there were substantial changes in performance. Figure 7.2 shows Purdue Probe Diagrams (PPD) for Harding St. and Wicker Rd. for the pre-pandemic and pandemic periods analyzed between 07:00 and 07:15 AM.

It was found that the connected vehicle volume decreased approximately 17%, AOG increased by 53%, LOS improved from F to C, and SF was reduced by 19% during a morning period at one of the studied intersections. These analysis tools can be immediately applied to more routine traffic engineering tasks such as prioritizing arterials for re-timing, adjusting time of day plan schedules, and before/after studies to assess impact of re-timing, system upgrades, network changes, or new developments.

7.2 Impact of Long-Term Interstate Construction Diversion on Traffic Signal Performance Measures

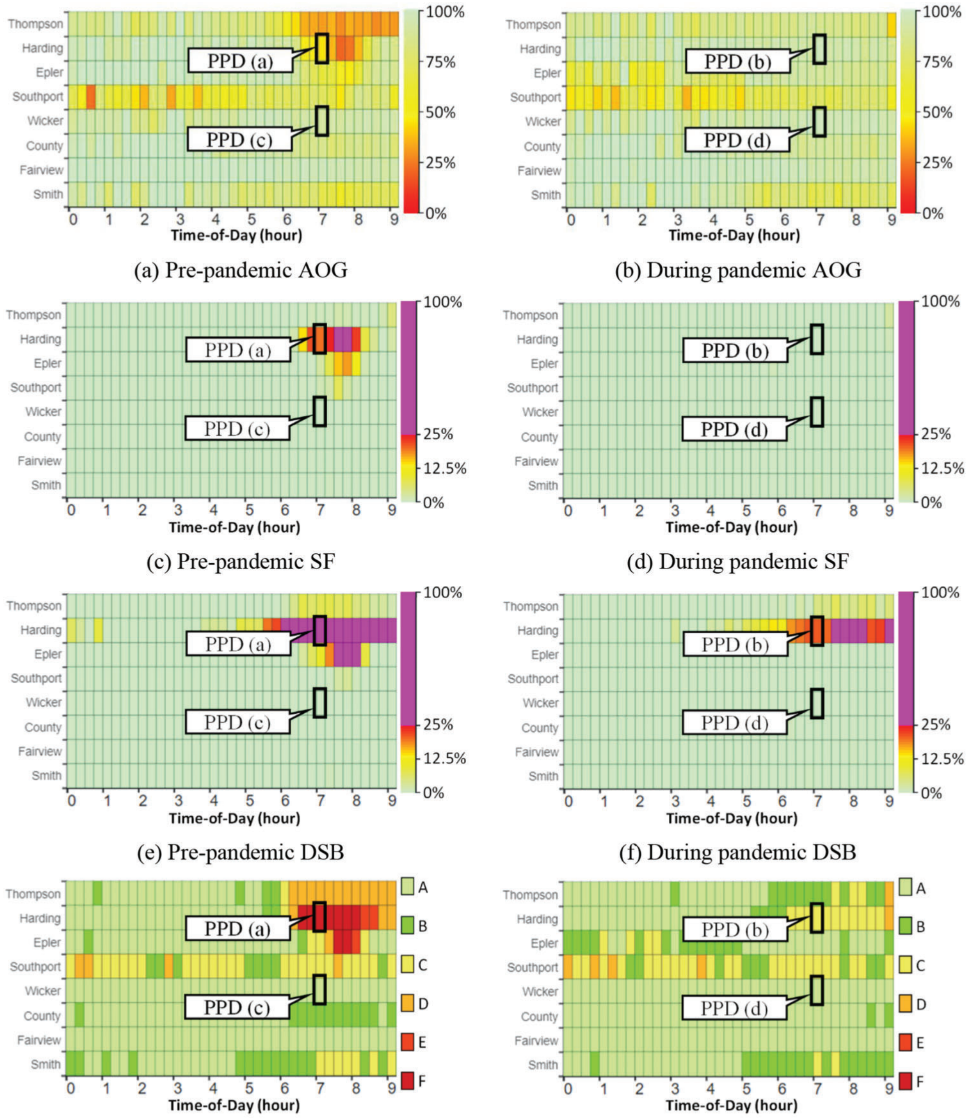
Local arterials can be significantly impacted by diversions from adjacent work zones. These diversions often occur on unofficial detour routes due to guidance received on personal navigation devices. Often, these routes do not have sufficient sensing or communication equipment to obtain infrastructure-based traffic signal performance measures (Day et al., 2014), so other data sources are required to identify locations being significantly affected by diversions.

A study was conducted to examine the network impact caused by the start of an 18-month closure of the I-65/70 interchange (North Split), which usually serves approximately 214,000 vehicles per day in Indianapolis, IN. In anticipation of some proportion of the affected vehicles diverting from official detour routes to local streets, a monitoring program was established to provide daily performance measures for over 100 intersections in the area without the need for vehicle sensing equipment. Instead, private sector CV trajectory data is used. The CV trajectory data consists of individual vehicle waypoints with a reporting interval of 3 seconds and a positional accuracy of a 1.5-meter radius. Every waypoint has the following attributes: GPS location, timestamp, speed, heading, and an anonymous unique trajectory identifier.

For this study, approximately 130 thousand trajectories and 2 million GPS points that traversed 13 of the most impacted signals on an alternative arterial (West St.) were analyzed to identify locations and time of day where operations are most affected. The following performance measures were estimated at the study locations for an 11-week period (Saldivar-Carranza, 2021; Saldivar-Carranza et al., 2021).

- *Sampled volumes*: count of unique trajectory identifiers of vehicles that crossed through the analyzed intersections for different movements. The change in sampled volumes provide practitioners with an estimation of increased demand.
- *Arrivals on green (AOG)*: the percentage of sampled vehicles experiencing AOG is a useful metric when assessing the level of progression at a particular location. A vehicle trajectory is categorized as having arrived on green to a traffic signal if it does not stop before crossing through the intersection.
- *Split failures (SF)*: the percentage of vehicles experiencing SF is a critical measurement that quantifies the occasions in which the traffic signal did not provide enough split (green) time for the stored queue to discharge. SF is identified from CV data when a vehicle stops more than once before crossing through the intersection. High levels of split failures indicate that an approach is operating at overcapacity.
- *Downstream blockage (DSB)*: the percentage of sampled vehicles experiencing DSB is an important indicator that describes the level at which an adjacent intersection is affecting the progression at the studied location.
- *Level of service (LOS)*: the traditional Highway Capacity Manual (HCM) LOS categorizes a location based on the experienced control delay (TRB, 2010).
- *Corridor-wide travel time*.

Figure 7.3 and Figure 7.4 show the estimated performance measures at the studied locations for vehicles traveling southbound 1 week before and week after the North Split closure.



(a) Pre-pandemic AOG

(b) During pandemic AOG

(c) Pre-pandemic SF

(d) During pandemic SF

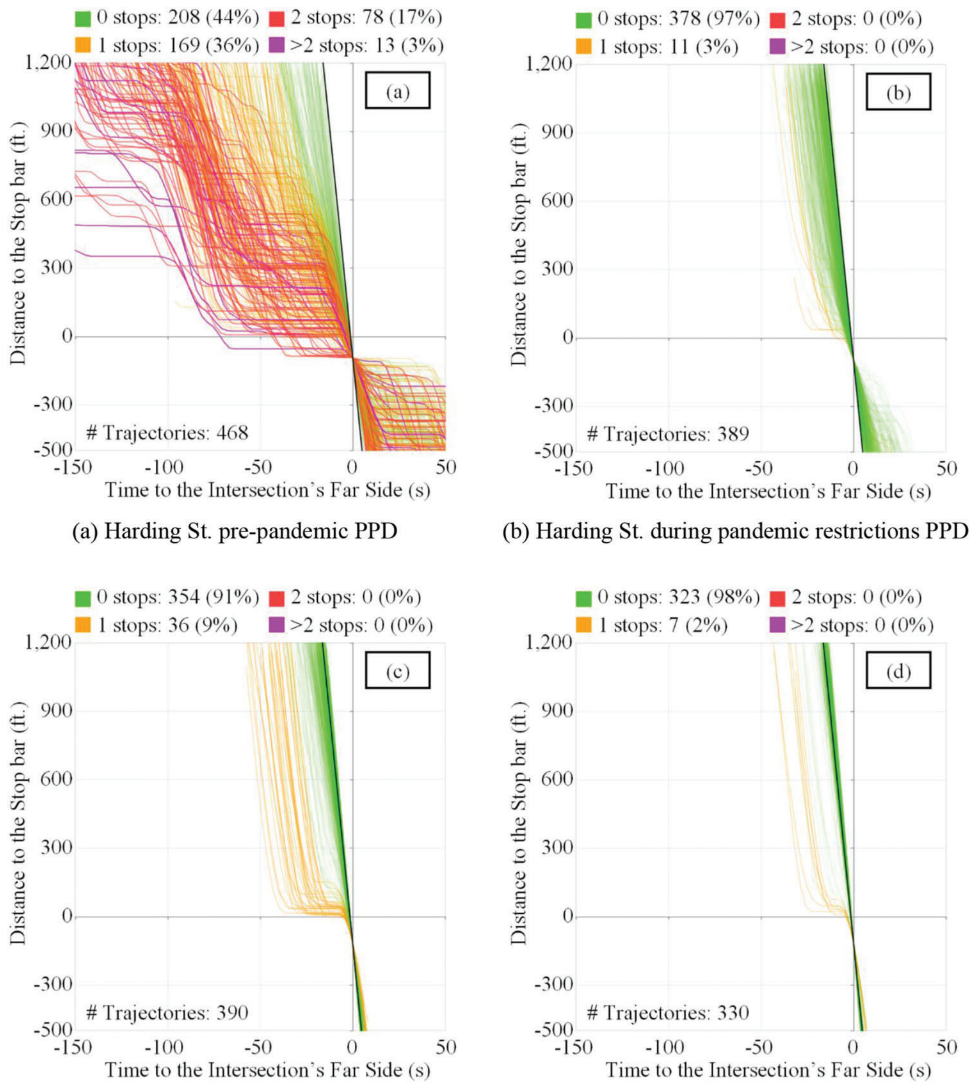
(e) Pre-pandemic DSB

(f) During pandemic DSB

(g) Pre-pandemic LOS

(h) During pandemic LOS

Figure 7.1 On-demand visualization of four critical intersection metrics for vehicles traveling northbound from January 6–31, 2020 weekdays (pre-pandemic) and June 1–26, 2020 weekdays (during pandemic).



(a) Harding St. pre-pandemic PPD

(b) Harding St. during pandemic restrictions PPD

(c) Wicker Rd. pre-pandemic PPD

(d) Wicker Rd. during pandemic restrictions PPD

Figure 7.2 Purdue probe diagrams referenced in Figure 7.1 from 07:00–07:15 AM.

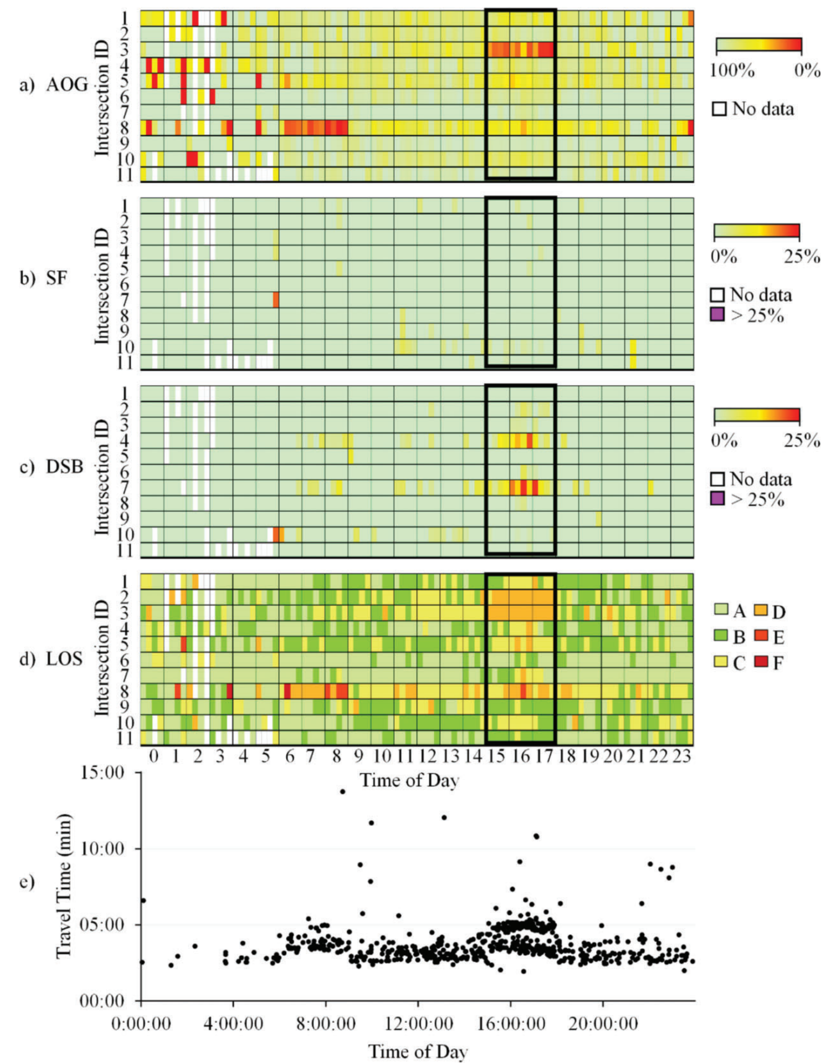


Figure 7.3 Signal performance measures and travel time 1 week before the North Split closure (May 10–14, 2021) for vehicles traveling southbound: (a) AOG, (b) SF, (c) DSB, (d) LOS, and (e) travel time.

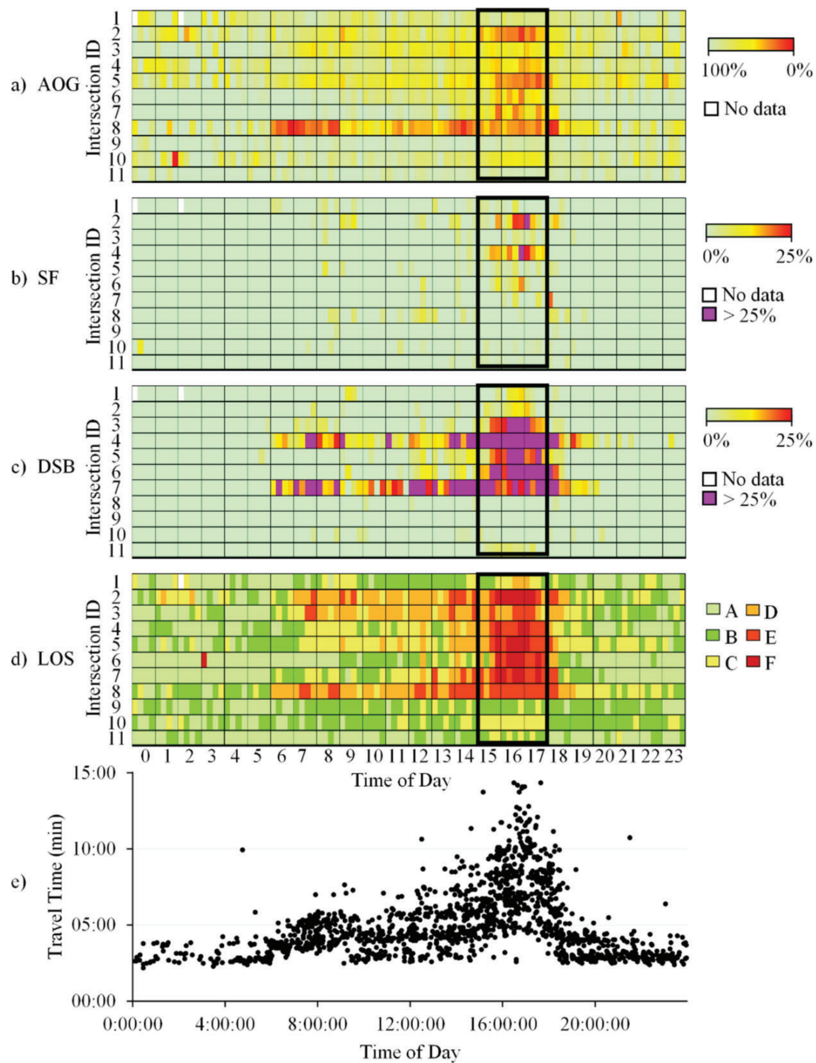


Figure 7.4 Signal performance measures and travel time 1 week after the North Split closure (May 17–21, 2021) for vehicles traveling southbound: (a) AOG, (b) SF, (c) DSB, (d) LOS, and (e) travel time.

From the analyzed data, it was observed that weekly afternoon peak period volumes increased by approximately 455% and median travel times grew by 74%. Specific operational failure modes that contributed to this deterioration in performance include the following.

- 3% increase on SF, indicating an increment of traffic signals operating at overcapacity.
- 10% increase on DSB, indicating there was queue spillback from downstream traffic signals.
- 16% decrease on AOG, indicating there were opportunities to improve traffic signal coordination.

8. WORKSHOPS AND TRAINING

There were several engagement activities carried out during this project that involved workshops, trainings, and support for INDOT stakeholders. Table 8.1 and Figure 8.1 provides a brief description of the engagement activities.

TABLE 8.1
Engagement activities

Date	Facility	Purpose
May 18, 2020	Webinar	Discuss with Terry Treon and ISP colleagues workshop for using tools.
July, 2020	Indianapolis TMC	Discuss progress on setting up monitors.
July 15, 2020	Purdue Traffic Lab	Work with Doug Meyer and his team on setting up TMC connectivity in Traffic Lab.
Sep 09, 2020	Seymour District	Setup dashboard, monitors and perform training.
Sep 18, 2020	Crawfordsville District	Setup dashboard, monitors and perform training.
Apr 26, 2021	Webinar	Presented webinar "Protect the Queue" conducted by R&D for INDOT staff.
May 10, 2021	Webinar	Presented webinar "INDOT Dashboards" conducted by R&D for INDOT staff.
June 15, 2021	Indianapolis TMC	Discuss current suite of dashboards and tools made available to operators and management.
June 22, 2021	Boone Co Fairgrounds	Present Trajectory heatmap dashboard visualization to INDOT stakeholders.
June 29, 2021	Webinar	INDOT Virtual Town Hall "Crowdsourced Connected Vehicle Data for Work Zone Performance Monitoring and Management."
Aug 10, 2021	Crawfordsville District	Routine maintenance and training.
Aug 10, 2021	Seymour District	Routine maintenance and training.
Aug 20, 2021	Purdue University	Campus visit by INDOT Executive Staff. Interactive dashboard demos on heatmaps, trajectories, winter operations and traffic signal analytics.

(a) Purdue Traffic Lab on July 15, 2020

(b) Boone County Fairgrounds on June 22, 2021

(c) Crawfordsville District Office on Aug 10, 2021

(d) Seymour District Office on Aug 10, 2021

Figure 8.1 Engagement with stakeholders.

9. SUMMARY AND RECOMMENDATIONS

Dashboards using segment data have been widely used in several states (Desai et al., 2020; FHWA, 2020a; Kim et al., 2020; Mathew, 2017; Schultz et al., 2019). However, the utilization of enhanced trajectory-based data is still in its early stages. Over 400 billion enhanced probe vehicle records are now available per month that state and federal governments can integrate into their monitoring, management, and infrastructure investment decisions. The following techniques and applications using big data were presented in this research.

- Visualizing interstate queues.
- Identifying back-of-queue hard braking events and crashes.
- Identifying alternate diversions during incidents and road closures.
- Agile management of work zones.
- Estimating traffic signal performance measures without infrastructure investment.
- Understanding impact of construction diversions on traffic signals performance.

The framework presented in this research will serve as a valuable tool for agencies to deploy connected vehicle performance measures for both Interstate and arterial routes, without significant investment in traditional ITS sensors. Since these techniques are based upon emerging commercially available connected vehicle data, they can be readily scaled to any construction project in the nation.

Additionally, the analysis and techniques discussed in this research on traffic signals will serve as a framework for any agency that wants to assess traffic signal performance at hundreds of locations with little or no existing infrastructure to prioritize tactical retiming and/or longer-term infrastructure investments. The calculated performance measures can be applied to any location in the world where connected vehicle trajectory data is available.

The web dashboards and tools developed using this data continue to evolve daily. Several workshops and trainings on the dashboard and suites were conducted for a variety of stakeholders and users. Multi-monitor displays were also installed at INDOT district offices and facilities that helps provide streamlined operation for TMC operators to rapidly identify relevant ITS cameras corresponding to incident and track the development and recovery.

REFERENCES

Bagdadi, O. (2013). Assessing safety critical braking events in naturalistic driving studies. *Transportation Research Part F: Traffic Psychology and Behaviour*, *16*, 117–126. https://doi.org/10.1016/j.trf.2012.08.006

Bagdadi, O., & Várhelyi, A. (2013). Development of a method for detecting jerks in safety critical events. *Accident Analysis and Prevention*, *50*, 83–91. https://doi.org/10.1016/j.aap.2012.03.032

Day, C. M., Bullock, D. M., Li, H., Remias, S. M., Hainen, A. M., Freije, R. S., Stevens, A. L., Sturdevant, J. R., & Brennan, T. M. (2014). *Performance measures for traffic signal systems: An outcome-oriented approach*. JTRP Affiliated Report. https://doi.org/10.5703/1288284315333

Desai, J., Li, H., Mathew, J. K., Cheng, Y.-T. Habib, A., & Bullock, D. M. (2021). Correlating hard-braking activity with crash occurrences on interstate construction projects in Indiana. *Journal of Big Data Analytics in Transportation*, *3*, 27–41. https://doi.org/10.1007/s42421-020-00024-x

Desai, J., Mathew, J. K., Kim, W., Liu, M., Li, H., Brooks, J. D., & Bullock, D. M. (2020). *Dashboards for real-time monitoring of winter operations activities and after-action assessment.* JTRP Affiliated Reports, Paper 33. https://docs.lib.purdue.edu/jtrpaffdocs/33/

Downing, R. (2020, October 20). *5 Reasons why companies choose connected vehicle data over mobile data.* Wejo. Retrieved November 16, 2020, from https://www.wejo.com/press/5-reasons-why-companies-choose-connected-car-data-over-mobile-data

FHWA. (2020a, April 23). *Applying archived operations data in transportation planning: A primer* [Webpage]. Federal Highway Administration. Retrieved November 18, 2020, from https://ops.fhwa.dot.gov/publications/fhwahop16082/ch5.htm

FHWA. (2020b, November 4). *Traffic incident management (TIM) performance measurement: On the road to success* (Report No. FHWA-HOP-10-009). Federal Highway Administration. Retrieved November 16, 2020, from https://ops.fhwa.dot.gov/publications/fhwahop10009/tim_fsi.htm

FHWA. (2021a, June 28). *Crowdsourcing for advancing operations* [Webpage]. Federal Highway Administration. Retrieved September 28, 2021, from https://www.fhwa.dot.gov/innovation/everydaycounts/edc_6/crowdsourcing.cfm

FHWA. (2021b, April 23). *Crowdsourcing for operations* [Webpage]. Federal Highway Administration. Retrieved September 28, 2021, from https://www.fhwa.dot.gov/innovation/everydaycounts/edc_5/crowdsourcing.cfm

Google. (n.d.a). *BigQuery: Pricing*. Google Cloud. Retrieved November 18, 2020, from https://cloud.google.com/bigquery#section-11

Google. (n.d.b). *Purdue University traffic research program cuts data analysis and batching from hours to minutes with BigQuery*. Google Cloud. Retrieved December 29, 2020, from https://cloud.google.com/customers/purduejtrp

Hunter, M., Mathew, J. K., Cox, E., Blackwell, M., & Bullock, D. M. (2021). *Estimation of connected vehicle penetration rate on Indiana roadways*. JTRP Affiliated Reports, Paper 37. https://doi.org/10.5703/1288284317343

INDOT TrafficWise [@TrafficWise]. (2021, July 1). Tweets [Twitter profile]. Retrieved July 10, 2021, from https://twitter.com/TrafficWise/status/1410685940520165378?s=20

ITSdigest. (2018, February 16). *470 Million connected vehicles on the road by 2025*. Retrieved January 4, 2021, from https://www.itsdigest.com/470-million-connected-vehicles-road-2025

Kim, W., Li, H., Mathew, J. K., & Bullock, D. M. (2020). Analytical techniques to use historical probe data to assess platooning potential on interstate corridors. *International Conference on Transportation and Development 2020*, pp. 284–295. https://doi.org/10.1061/9780784483138.025

Mathew, J., Krohn, D., Li, H., Day, C., & Bullock, D. (2017, April 28). *Implementation of probe data performance measures* (Publication PA-2017-001-PU WO 001). Pennsylvania Department of Transportation.

Mcnamara, M., Li, H., Remias, S., Richardson, L., Cox, E., Horton, D., & Bullock, D. M. (2015). Using real-time probe vehicle data to manage unplanned detour routes. *ITE Journal*, *85*(12), 32–37. https://www.ite.org/pub/?id=B772541B-04AB-0F6F-A863-34C8217C947E

Mekker, M. M., Remias, S. M., McNamara, M. L., & Bullock, D. M. (2020). *Characterizing interstate crash rates based on traffic congestion using probe vehicle data.* JTRP Affiliated Reports, Paper 31. https://docs.lib.purdue.edu/jtrpaffdocs/31/

Remias, S., Brennan, T., Grimmer, G., Cox, E., Horton, D., & Bullock, D. M. (2012). *2011 Indiana interstate mobility report—Full version*. Indiana Mobility Reports. https://doi.org/10.5703/1288284314680

Saldivar-Carranza, E. D. (2021, May). *Scalable operational traffic signal performance measures from vehicle trajectory data* [Master's thesis, Purdue University].

Saldivar-Carranza, E., Li, H., Mathew, J., Hunter, M., Sturdevant, J., & Bullock, D. M. (2021). Deriving operational traffic signal performance measures from vehicle trajectory data. *Transportation Research Record: Journal of the Transportation Research Board*, *2675*(9). https://doi.org/10.1177/03611981211006725

TRB. (2010). *Highway capacity manual* (5th ed.). Transportation Research Board.

Schultz, G. G., Saito, M., Hadfield, M. G., Bennett, L. S., & Eggett, D. L. (2019, April). *Analysis of performance measures of traffic incident management in Utah* (Report No. UT-19.01). Utah Department of Transportation. Retrieved from https://rosap.ntl.bts.gov/view/dot/42391

wejo. (2020). *Why Wejo* [Webpage]. Retrieved November 16, 2020, from https://www.wejo.com/why-wejo

APPENDICES

Appendix A. Weekly Work Zone Report

Appendix B. Weekly Interstate Hard Braking Report

APPENDIX A. WEEKLY WORK ZONE REPORT

Indiana's interstate system is analyzed in sections divided by INDOT districts by interstate as shown in Figure A.1 using the connected vehicle data. The report presents the summary of overall state for the past five weeks using daily trends of mile-hours of congestion (<45 MPH) and number of crashes grouped by districts as shown in Figure A.2. Similar trends are also shown using different speed bins and crash severity categories. The daily mile-hours of congestion, number of crashes and hard braking events by each work zone are also presented.

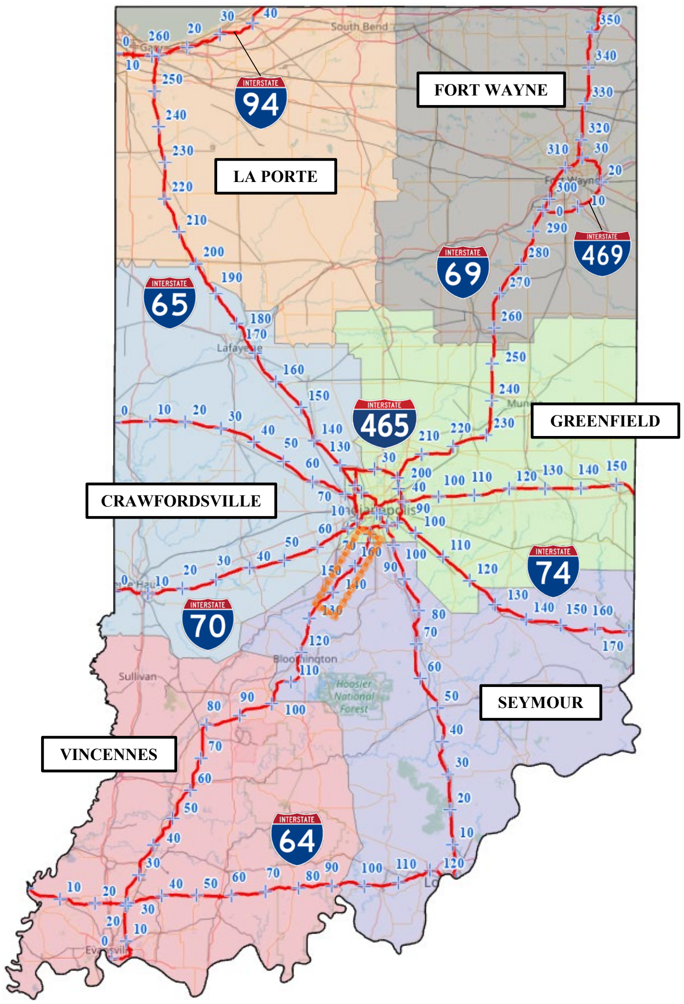
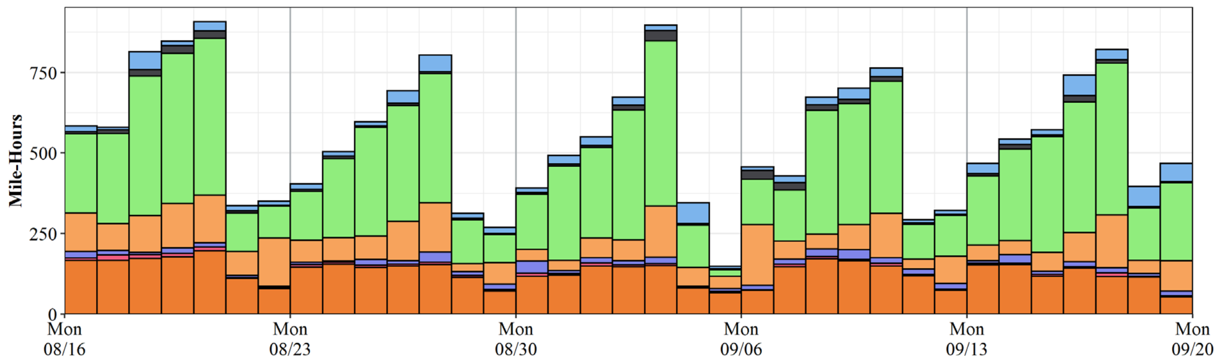


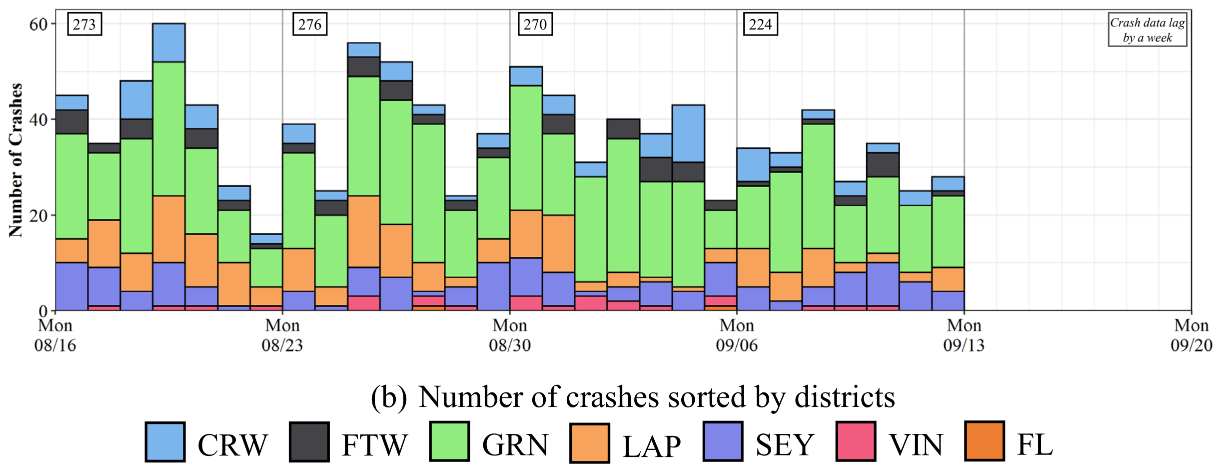
Figure A.1 Indiana's interstate system.

The report is then segregated into different districts section. Each section starts with the mile-hours of congestion and hard braking events within that district. Each interstate section by district is analyzed first using the 12 weeks view of heatmaps with crash events (Figure A.3) and hard braking events before comparing current week and previous week. Hard braking events by each mile section are compared staked by day of the week for the current and previous weeks.

Each work zone is then summarized by hours of queueing, total mile-hours below 45 MPH, worst day in terms of congestion and number of crashes.



(a) Mile-hours of congestion (< 45 MPH) by districts



(b) Number of crashes sorted by districts

Figure A.2 Daily trend of mile-hours of congestion and crashes for past 5 weeks by districts across all interstate in Indiana.

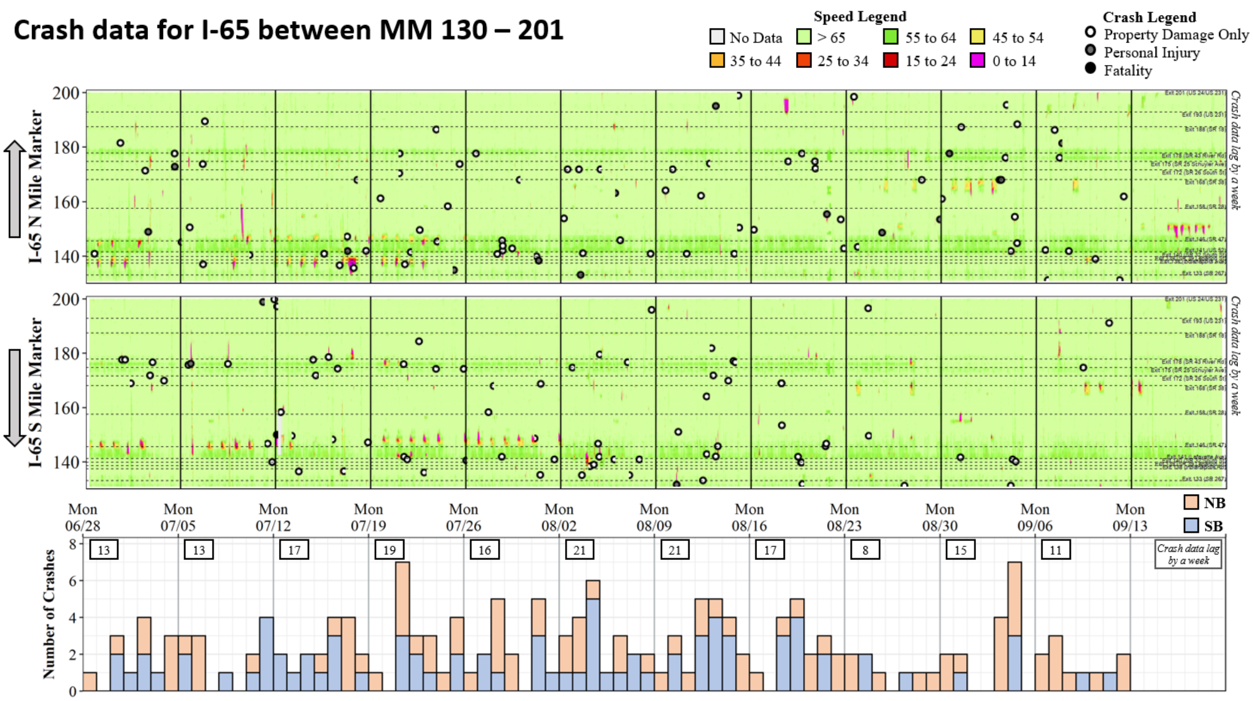


Figure A.3 Illustration of 12-week heatmap view along I-65 MM 130 to MM 201 in Crawfordsville with daily crash incidents by direction of travel.

APPENDIX B. WEEKLY INTERSTATE HARD BRAKING REPORT

Utilizing the connected vehicle event data, specifically hard-braking event data points involving deceleration of greater than 2.67 m/s^2, a spatial and temporal visualization of hard-braking activity on Indiana's entire interstate network can be created. This systemwide as well as route-wise visualization of hard-braking activity provides practitioners and state agencies alike with the ability to pinpoint hotspots of potential conflict situations at a glance, in near real-time, thus providing an opportunity to implement corrective measures to aid the safe flow of traffic.

A sample visualization of hard-braking activity aggregated by mile marker and stacked by day of week for the week of August 30, 2021, on Interstate 465 (I-465), a commuter beltway around the city of Indianapolis, is depicted in Figure B.1 below. Callouts are added to those 1-mile segments of interstate exhibiting the most improvement in terms of aggregated hard-braking event counts. Similarly, segments exhibiting highest increase in hard-braking event counts are also pointed out for each interstate highlighting locations of concern that should see prioritized attention from contractors and state agencies in terms of implementing safety improvements.

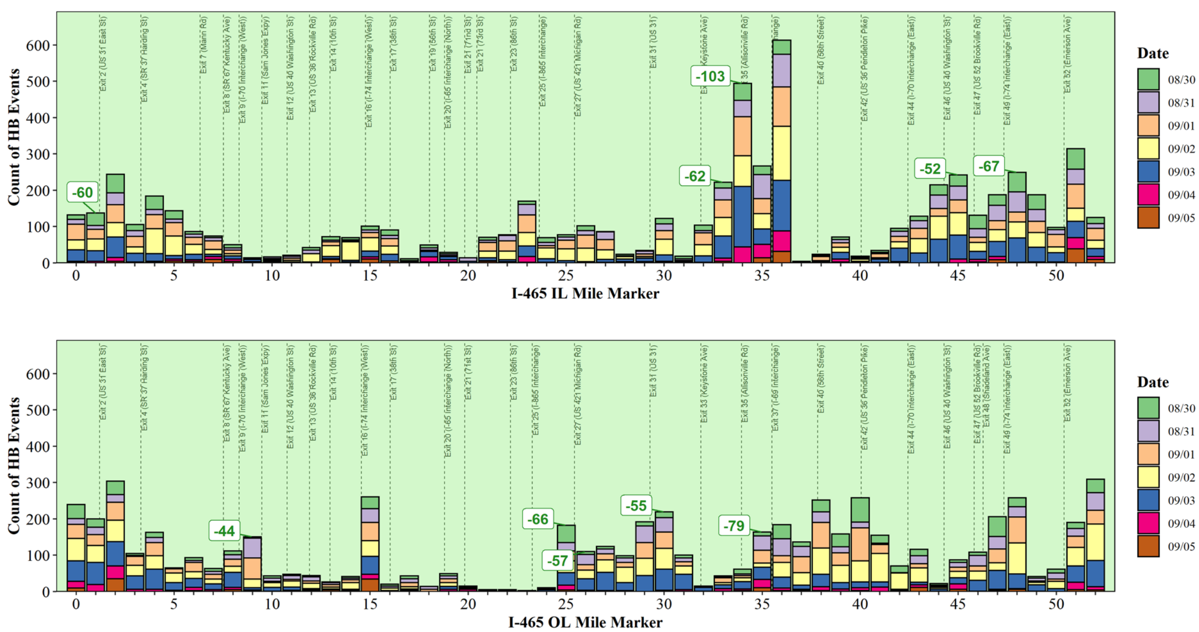


Figure B.1 Hard-braking Report for I-465 for the week of August 30, 2021.

An additional graphic generated on a weekly basis, such as the one depicted in Figure B.2 below shows the five 1-mile segments around the state of Indiana which saw the most rise in hard-braking activity. This presents a statewide look (in addition to earlier route-wise views) at areas of concern especially in areas where the public right of way is impacted due to construction activity.

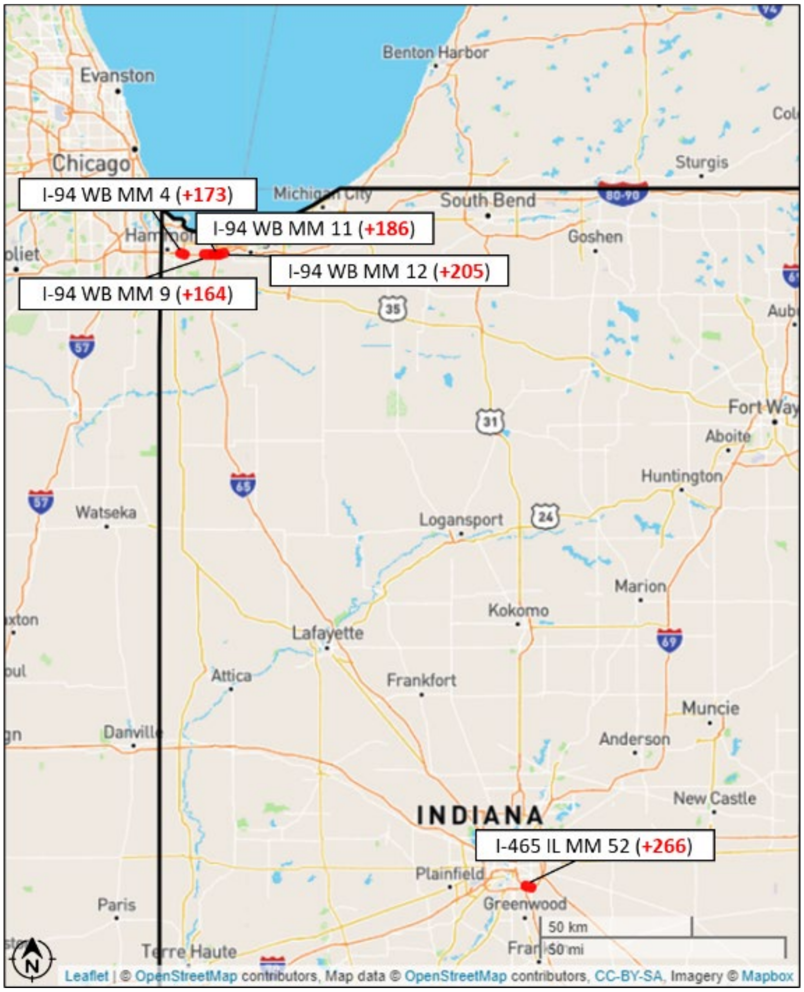


Figure B.2 Top five 1-mile interstate segments with highest increase in hard-braking activity for the week of September 6, 2021.

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.

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