AN ASSESSMENT OF CONNECTED VEHICLE DATA: THE EVALUATION OF INTERSECTIONS FOR ELEVATED SAFETY RISKS AND DATA REPRESENTATIVENESS

by

Margaret Hunter

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STATEMENT OF COMMITTEE APPROVAL

Dr. Darcy M. Bullock, Chair
Lyles School of Civil Engineering

Dr. Konstantina Gritzka
Lyles School of Civil Engineering

Dr. Jon D. Fricker
Lyles School of Civil Engineering

Approved by:
Dr. Dulcy Abraham

To my parents, Cindy and Jim, for all the love, support, and laughs for without which it would be a dull, confusing life.

To my brother, Ian, you and I already know you're awesome. Run fast.

To my uncle, Allen, for your quiet, calm mentorship and advice. Be good.

Finally, to my favorite idiots, Rory, Alfie, and MooMoo, for reminding me to cherish the small things and for making me smile every day.

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ABSTRACT

Historically, agencies have been reliant on physical infrastructure, crash data, manual data collection, and modeling to evaluate their road networks. Over the past several years, enhanced probe data has become commercially available and has shown itself to be a relatively inexpensive and scalable way to evaluate the performance of road networks. In January 2022 alone, 11.3 billion passenger vehicle trajectory waypoints and 279 million passenger vehicle event records were logged in the state of Indiana. This data, typically segmented into vehicle trajectory waypoints and vehicle event records, contains a variety of information including, but not limited to, location, speed, heading, and timestamp.

One use for this enhanced probe data is the evaluation of traffic signals for safety improvements. Typically, agencies require 3 – 5 years of crash data to be able to statistically identify intersections in need of safety improvements. This study compared crash data over a 4.5-year period at 8 signalized intersections to one month of weekday hard-braking and hard-acceleration data from July 2019. A Spearman's rank-order correlation test was used, and a strong to very strong correlation between event data and crashes could be found indicating that just one month of event data could be an adequate substitute for 3 – 5 years of crash data.

The representativeness of this data is often a major concern for many agencies as the usefulness of the data is only as good as the data itself. This paper describes and demonstrates a methodology for measuring connected vehicle penetration using data provided by state highway performance monitoring stations. This study looked at 1.7 billion count station vehicle counts and 70 million connected vehicle records across 381 count stations in 11 different states (California, Connecticut, Georgia, Indiana, Minnesota, North Carolina, Ohio, Pennsylvania, Texas, Utah, and Wisconsin). Across the 11 states and 381 stations, the average percent penetration was 3.8% in August 2020 and 3.9% in August 2021. Drilling down to August 2021, the percent penetration observed among the 187 interstate stations varied from 1.6% in Indiana to 10.0% in Wisconsin. A similar comparison of 162 non-interstate count stations showed a variation of 2.1% in MN and 18.0% in WI on non-interstates.

1. INTRODUCTION

Connected vehicle data is emerging as an important new data set for a variety of department of transportation (DOT) applications. One such example is the scalable evaluation of intersection performance measures. Removing the need for expensive infrastructure investments, connected vehicle data can provide several performance measures, such as arrival on green, downstream blockage, split failures, and level of service (E. Saldivar-Carranza et al., 2020). Similar analyses have been extended to include diverging diamonds and roundabouts (E. Saldivar-Carranza et al., 2022; E. D. Saldivar-Carranza et al., 2021). Another such use is the monitoring of highways for potential safety issues and safety improvements, especially within work zones. Studies using connected vehicle data have shown that speed feedback displays, digital speed limit trailers, presence lighting, and queue trucks have a positive impact on vehicle speeds and safety (Mathew et al., 2021; Sakhare, Desai, Mahlberg, et al., 2021; Sakhare, Desai, Mathew, et al., 2021). Additionally, as DOT's and legislatures look to the future of electric vehicles, connected vehicle data can provide a plethora of information regarding the usage of electric vehicles (Desai, Mathew, et al., 2021). Such information will be important in assisting decision makers with policy and infrastructure investments.

Crash data has historically been used to identify emerging safety issues at signalized intersections. However, collecting this data and implementing safety changes can take years. Event data, such as hard-braking and hard-acceleration data, has the potential to greatly reduce the data collection time. This thesis describes a use case for evaluating the correlation between crash data and hard-braking / hard-acceleration connected vehicle data and evaluates the relative penetration of connected vehicle data across 11 states. The remainder of this chapter and subsequent chapters are organized as follows:

- Chapter 1: Introduction and study motivation
- Chapter 2: Literature review
- Chapter 3: Background information on the study corridor
- Chapter 4: Crash data - introduction and analysis
- Chapter 5: Hard-braking and hard-acceleration event data - introduction and analysis
- Chapter 6: Correlation analysis between crash data and event data

- Chapter 7: Data representativeness evaluation across 11 states
- Chapter 8: Conclusion
- Appendix A: Data repository for connected vehicle penetration study
- Appendix B: Example percent penetration calculations for a station in each state

1.1 Study Motivation

The Indiana Department of Transportation (INDOT) has several ongoing projects that embrace the use of digital technologies. Such examples included the use of social media to alert road users of current road conditions, embedded weigh stations paired with roadside cameras to identify overweight trucks, and onboard truck telematics and real-time dashboards to assist with winter operations (Desai, Mahlberg, et al., 2021; INDOT, n.d.). However, identifying intersections in need of safety improvements remains an analog endeavor. Agencies are reliant on written crash reports which can be vague and dependent on witness accounts leaving the exact location unknown. Additionally, due to the relative infrequency of crashes, agencies need 3 – 5 years of crash data in order to ensure the validity and accuracy of the agency's models. However, this method is considered reactive as agencies must wait for a substantial crash history to develop as evidence for proceeding with safety improvement projects. There is a growing interest in the industry to replace the historical method with surrogate events to reduce the time between data collection and the implementation of safety improvements.

Since the 1960's, there has been interest in supplementing or replacing crash counts with traffic conflicts (Perkins & Harris, 1968). Conflicts occur more frequently than crashes and are caused by the same failures that result in crashes (Tarko, 2020). The higher number of conflicts combined with their similar causations to crashes make them attractive to agencies trying to statistically determine areas for safety improvements. However, conflicts have a disadvantage; they can be difficult to collect, require trained personnel, and can be dependent on the subjective ratings of the observer.

Crowdsourced probe data that provides average segment speeds has been commercially available for some time (Remias et al., 2013). Recent developments of probe data now include data elements such as hard-braking and hard-acceleration from onboard sensors (Ctrl-Shift & Wejo, 2020). This data, aggregated by third-party vendors, can provide agencies with the exact time and location of events on their roadways (Hunter, Saldivar-Carranza, et al., 2021).

In July 2019, there were over 6 million hard-braking events (Figure 1.1b) and over 10 million hard-acceleration events in Indiana. In contrast, during the same month, there were only 17,652 crashes in Indiana (Figure 1.1a), which represents 0.3% and 0.2% of the total number of hard-braking events and hard-acceleration events, respectively. In addition to the fewer number of crashes, crash reports may be incomplete or unclear. Between 2020 and 2021, 81.5% of crash records were missing the roadway id and/or the mile marker. Event data, on the other hand, provides the exact time and location of the event. The motivation of this study is to use emerging crowdsourced event data for agency-wide screening of intersections and approaches for potential safety improvements, so agencies can follow up with mitigation measures addressing emerging problems much quicker than typical practices that rely on 3-5 years of crash data (Hunter, Saldivar-Carranza, et al., 2021).

(a) In July 2019, there were 17,652 crashes in Indiana.

(b) In July 2019, there were 6,172,453 hard-braking events in Indiana.

Figure 1.1. Visualization of number of events in Indiana in July 2019 (Hunter, Saldivar-Carranza, et al., 2021)

2. LITERATURE REVIEW

This chapter presents a literature review on the current understanding of surrogate crash events and connected vehicle data. Understanding the current state of the practice was important in understanding where this study fit and developing ways to improve it.

2.1 Surrogate Crash Events

In the early years of traffic conflict analysis, a traffic conflict was defined as the occurrence of an evasive maneuver, braking, or a lane change (Older & Spicer, 1976). Although there are many studies that analyze traffic conflicts, few have looked at hard-braking and hard-acceleration events at a large scale. Bagdadi and Varhelyi presented the critical jerk method to differentiate between critical and potentially critical events (Bagdadi & Várhelyi, 2013). In a following paper, Bagdadi compared the critical jerk method to the longitudinal acceleration method in a naturalistic driving study focused on safety critical braking events. The study concluded that the critical jerk method was about 1.6 times better than the longitudinal acceleration method at identifying near-crashes (Bagdadi, 2013). Stipancic, et al. compared hard-braking events and hard-accelerating events to crash frequency for links and intersections. For both hard-braking events and hard-acceleration events, a positive correlation was found between the number of events and crash frequency for both links and intersections; however, the correlation was stronger for intersections (Stipancic et al., 2018). Li, et al. analyzed roughly 1.5 million crowd sourced hard-braking events at signalized intersections, work zones, interchanges, and entry/exit ramps. The study concluded that dilemma zones could be identified by hard-braking events along with work zones that may be in need of geometry changes or more advanced warning signs (Li et al., 2020).

Using video camera footage, Essa and Sayed concluded that the highest frequency of traffic conflicts occurred at the beginning of green as the queue is discharged at a low speed while vehicles joining the queue approach at a high speed; nevertheless, they considered most of these conflicts to be low-severity (Essa & Sayed, 2019). While Mekker, et al.'s study focused on free flow and congested conditions on interstates, the study determined that a crash was approximately 24 times more likely to occur in congested conditions than in free-flowing conditions (Mekker et al., 2014). One common cause of congestion on interstates is construction activity. Desai, et al.

found that, in and around interstate work zones, there was approximately 1 crash/mile for every 147 hard-braking events (Desai et al., 2020a).

Chapters 3 – 5 expand on a previously published paper looking at the relationship between hard-braking and crashes along SR-37. These chapters also consider hard-acceleration and add additional time bins to attempt to improve the correlation between hard-braking and hard-acceleration events (Hunter, Saldivar-Carranza, et al., 2021).

2.2 Connected Vehicle Data

Connected vehicle data is just the latest in the evolution of vehicle data. As early as 1999, GPS based travel time data was used to evaluate agency infrastructure in Louisiana (Quiroga & Bullock, 1998). By the early 2010s, crowdsourced vehicle probe data became available to both drivers and agencies through many providers and smartphone applications (INRIX, n.d.; Levine, 2019; Wang, 2007). While data gathered from smartphones was the main component to this crowdsourced data, some providers incorporated GPS-enabled vehicles as well (Hoseinzadeh et al., 2020; Kim & Coifman, 2014). In the following years, many studies have been conducted to understand the accuracy of these datasets. These studies include a study conducted on 2,500 miles of roadway on and around I-95 evaluating commercially provided travel time and speed data (Haghani et al., 2009), a two-month study comparing probe data speeds to speeds obtained from loop detectors (Kim & Coifman, 2014), studies comparing probe data to Bluetooth sensors with a focus on arterials and surface streets (Hoseinzadeh et al., 2020; X. Zhang et al., 2015), and a multi-year study comparing probe data to radar sensors (Ahsani et al., 2019).

These past iterations of vehicle data have been well tested and have been validated for many years. Connected vehicle trajectory data, which contains individual vehicle locations, timestamp, speed, and heading from onboard sensors, however, is still in the pilot phase for many agencies. Over the past several years, many studies focused on creating methodologies for evaluating road networks at low penetration. One study presented a method, tested against simulations and real-world data, for estimating queue length and traffic volumes without needing to explicitly know the market penetration (Zhao et al., 2019). A study conducted by Zhang et al. found that a 4% penetration was sufficient to improve ramp metering performance (C. Zhang et al., 2019). However, studies by Day et al. found that aggregated data at penetration levels as low as 0.09% - 0.8% would provide acceptable levels of representation for corridor retiming given a large enough aggregation period (Day et al., 2017; Day & Bullock, 2016).

While connected vehicle data has led to the creation of new techniques to evaluate road networks (Desai et al., 2020b; Hunter, Saldivar-Carranza, et al., 2021; Li et al., 2019, 2020; Ma et al., 2020; E. Saldivar-Carranza et al., 2020; Waddell et al., 2020), there are few studies looking at connected vehicle penetration rates. In 2016, Li et al. compared loop detectors counts to vehicle trajectory counts and found an average percent penetration of 1.1% with a range of 0.2% to 2.0% depending on the time of day (Li et al., 2016). Chapter 7 of this paper expands upon two previous papers. The first paper analyzed the percent penetration for 3 months in 2020 in Indiana and found interstates to have an average percent penetration of 4.3% and non-interstates to have an average percent penetration rate of 5.0% (Hunter, Mathew, Cox, et al., 2021). The second paper extended the geographic analysis area to include Ohio and Pennsylvania and a total of 54 count station locations. The study found for August 2020, the average percent penetration ranged from 3.9% in Pennsylvania to 4.6% in Indiana (Hunter, Mathew, Li, et al., 2021). Utilizing a similar methodology, Chapter 7 continues to expand the number of count stations and number of states.

3. STUDY CORRIDOR

This study utilizes weekday event data collected between July 1 and July 31, 2019, at 8 intersections along a corridor on SR-37, south of Indianapolis, IN (Figure 3.1a, callout i). The corridor is a 4 to 6-lane principal arterial with a speed limit of 55 mph. The volume along the corridor varies between 64,000 vehicles/day at the northernmost intersection, 49,000 vehicles/day in the middle of the corridor, and 38,000 vehicles/day at the southernmost intersection. Indianapolis commuters living south of the city use this corridor to commute northbound in the morning and southbound in the evening. The studied intersections (Figure 3.1b), in north to south order, are Thompson Rd., Harding St., Epler Ave., Southport Rd., Wicker Rd., County Line Rd., Fairview Rd. and Smith Valley Rd. These intersections run on an actuated-coordinated operation, most of them with a cycle length of 120 seconds, across four different weekday time-of-day (TOD) plans (Hunter, Saldivar-Carranza, et al., 2021):

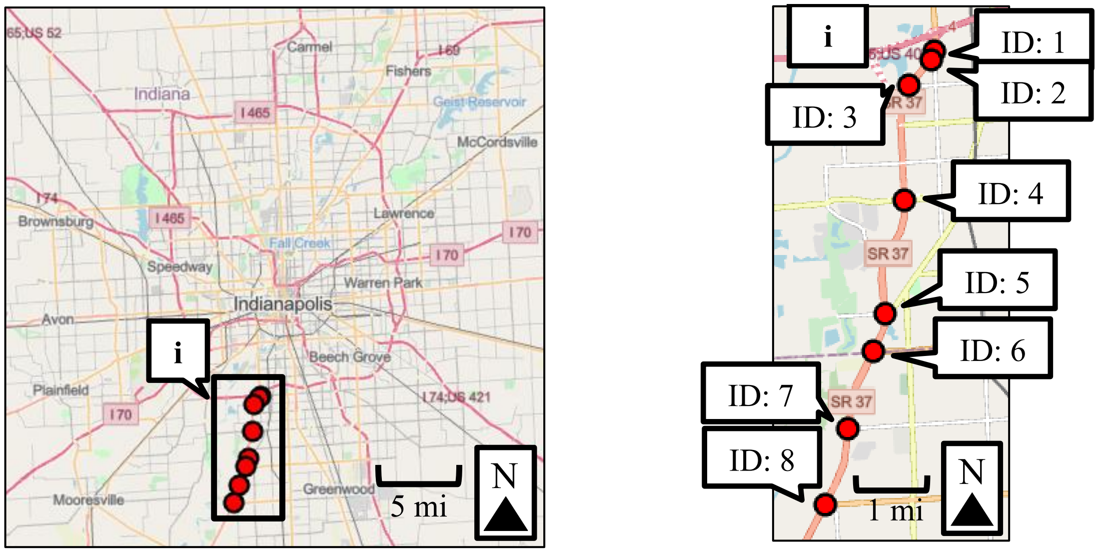
AM Peak (AM): 05:00 – 09:15

Mid-day (MD): 09:15 – 14:30

PM Peak (PM): 14:30 – 19:00

Evening (EV): 19:00 – 22:00

An additional detail of note is that intersection 2, Harding St., in the southbound direction operates on a contestant green signal.

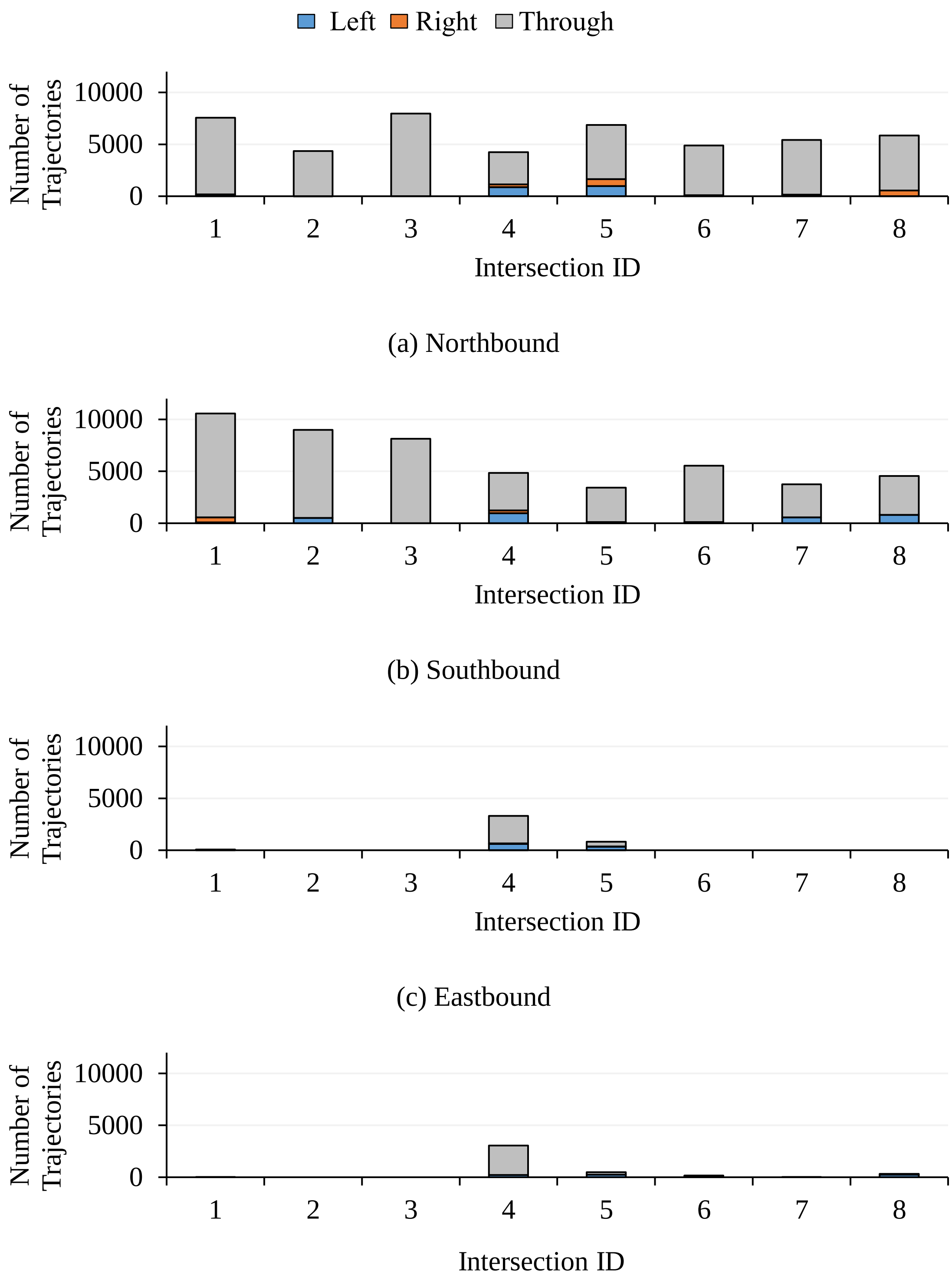


(a) Location of study corridor

(b) Study corridor shown with intersection labels

Figure 3.1. Corridor location for hard-braking and hard-acceleration event study

The number of vehicle trajectories along the corridor varies between 823 trajectories/day at the northernmost end, 414 trajectories/day in the middle, and 472 trajectories/day at the southernmost end. Figure 3.2 presents the number of weekday trajectories to traverse each intersection by movement type in July 2019. Noticeably, the vast majority of vehicles travel straight through the intersections instead of turning. Additionally, intersections 4 and 5 stand out as having the most cross traffic (Figure 3.2c and Figure 3.2d).



(a) Northbound

(b) Southbound

(c) Eastbound

(d) Westbound

Figure 3.2. Number of weekday trajectories to enter the intersections by movement type for July 2019

4. CRASH EVENTS

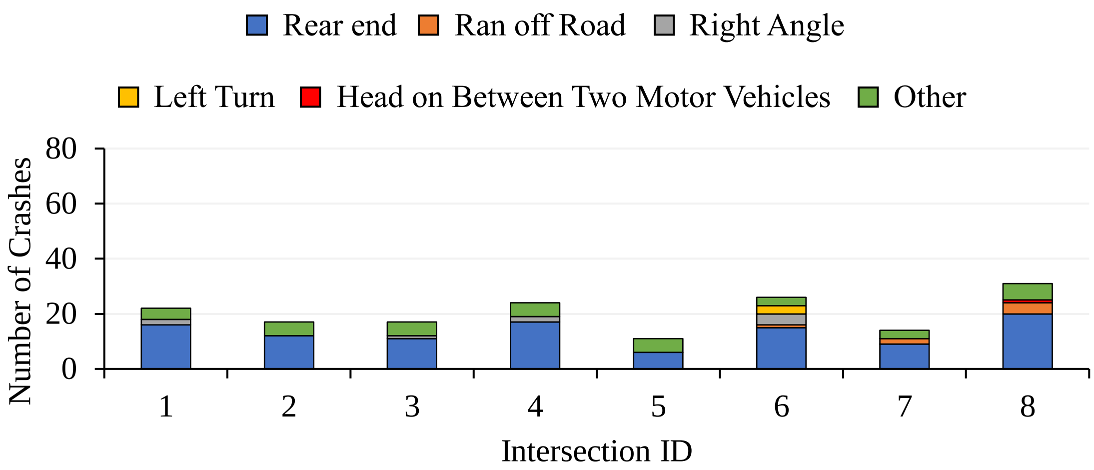
4.1 Crash Data

The crash counts were aggregated by intersection using information gathered from Indiana's online crash repository. Using the provided GPS information, crashes that were located along the corridor within 1320 ft of an intersection were assigned to that intersection. Crashes that were missing geolocation information were manually assigned to intersections on the study corridor, if applicable, by reading through the crash report's narrative. Crashes were then filtered by their different attributes, such as their recorded manner of collision, direction of travel, and time of day.

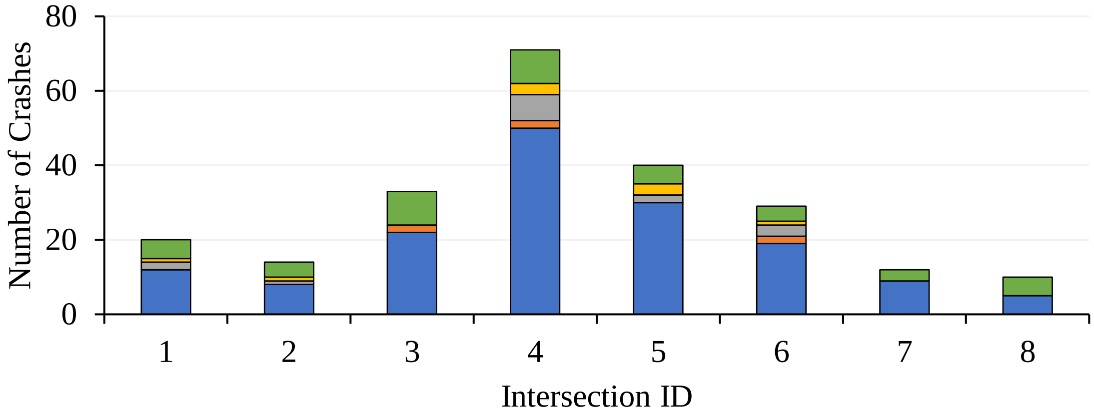
In Indiana, during July 2019, 17,652 crashes were reported, of which 24 occurred along the roughly 6.5-mile study corridor. 10 of those 24 crashes occurred in the vicinity of an intersection. As agencies need 3 – 5 years of crash data in order to have enough crash data to perform a statistical correlation test, this study collected crash data for a 4.5-year period between January 1, 2016 and July 9, 2020. This increased the intersection crash count to 551 crashes, of which 391 were weekday crashes. Of the 391 weekday crashes, 261 of those indicated a rear-end collision and 24 indicated a right-angle collision (Hunter, Saldivar-Carranza, et al., 2021).

4.2 Analysis: Crash by Manner of Collision

Figure 4.1 shows a stacked bar graph of the number of crashes categorized by manner of collision that occurred adjacent to the 8 intersections along SR-37 on weekdays during the 4.5-year study period. The southbound approach of intersection 4, Southport Rd., stands out as having the most crashes (71 crashes) for the 4.5-year period. Of those 71 crashes, 70% were rear-end collisions. Likewise, the second and third highest crash count approaches, southbound intersection 5, Wicker Rd., and northbound intersection 8, Smith Valley Rd., have 75% and 65%, respectively, of their total crash count as rear-end crashes. Overall, 65% of the 391 recorded weekday crashes on this corridor were rear-end collisions. Right-angle collisions were less frequent and only accounted for 24 of the 391 weekday crashes (6%), with the most right-angle collisions occurring at intersection 4, Southport Rd. (2 in NB and 7 in SB), and intersection 6, County Line Rd. (4 in NB and 3 in SB) (Hunter, Saldivar-Carranza, et al., 2021).



(a) Northbound

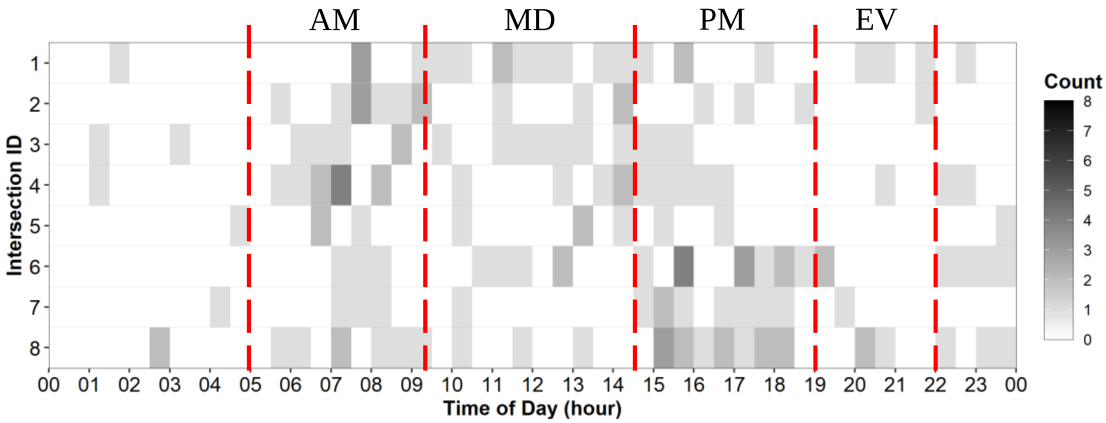


(b) Southbound

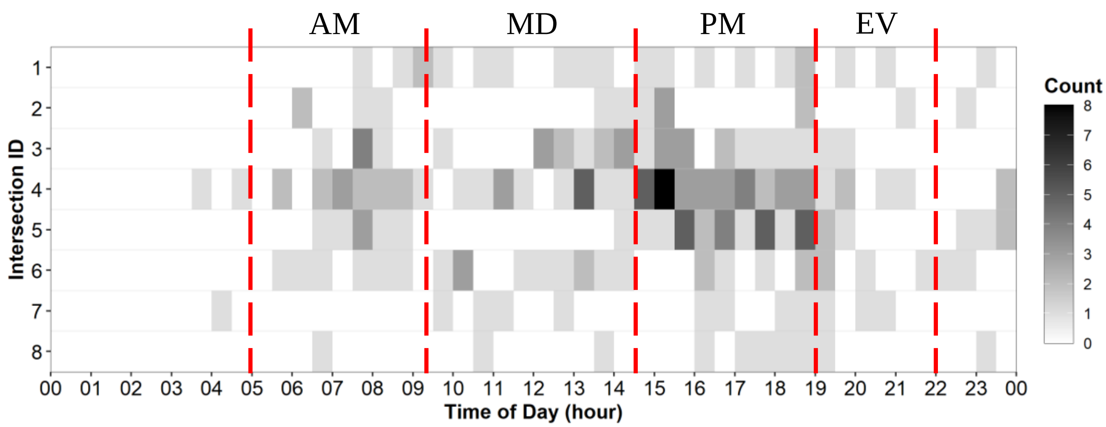
Figure 4.1. Number of weekday crashes by intersection and manner of collision on SR-37 between January 1, 2016 and July 9, 2020 (Hunter, Saldivar-Carranza, et al., 2021)

4.3 Analysis: Crashes by Time of Day

Figure 4.2 presents a heatmap of weekday crashes aggregated over the study period. Crashes were binned by 30-minute periods and assigned to their respective intersections. In the southbound approach (Figure 4.2b), intersection 4, Southport Rd., and intersection 5, Wicker Rd., stand out in the PM time frame as having a relatively large number of crashes (Hunter, Saldivar-Carranza, et al., 2021).



(a) Northbound



(b) Southbound

Figure 4.2. Heatmap of frequency of weekday crashes between January 1, 2016 and July 9, 2020 (Hunter, Saldivar-Carranza, et al., 2021)

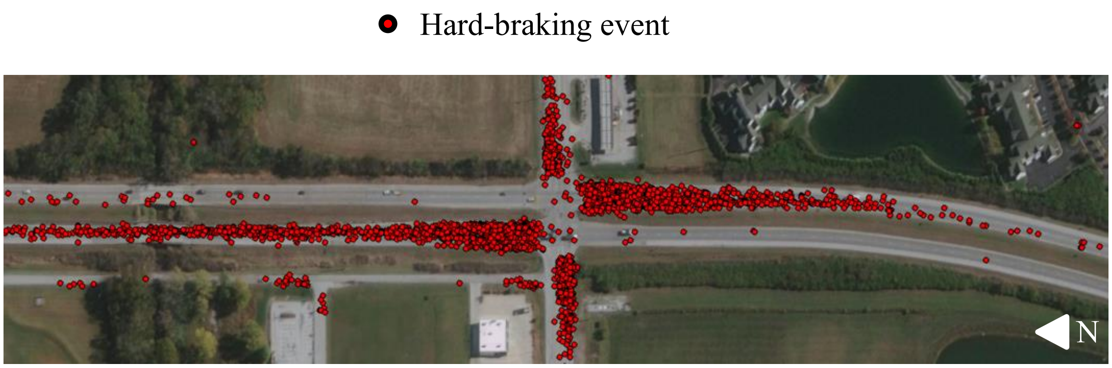
5. EVENT DATA: HARD-BRAKING AND HARD-ACCELERATION

5.1 Data

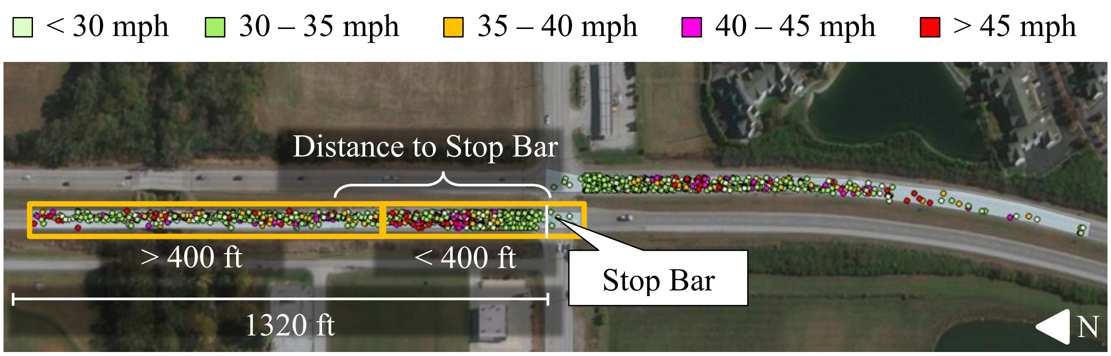
The event data used in this study was made commercially available by a data provider that works directly with the original equipment manufacturers (OEMs). The enhanced probe data from these connected passenger vehicles included an anonymized unique identifier along with timestamp, geolocation, speed, heading, and event description, such as hard-braking/acceleration (Note: Connected vehicles, in this paper, are defined as any vehicle that sends information to another vehicle, a roadside unit, or it's manufacturer). The provider of this data defined hard-braking and hard-acceleration events as any vehicle deceleration or acceleration with a magnitude greater than 8.76 ft/s^2 (0.272 g). In July 2019, over 6,000 hard-braking events occurred along SR-37 within 1320 ft of the 8 intersections. Likewise, over 11,000 hard-acceleration events occurred. The penetration level of this data is estimated to be around 2% (Hunter, Saldivar-Carranza, et al., 2021).

5.2 Methodology

The events analyzed in this paper were sorted by intersection, distance from stop bar, and speed at which the vehicle was traveling when the event occurred. In this study, the analysis was limited to through movements. A geofence region was drawn along the through lanes for each approach. This upstream region began parallel to the opposing direction's stop bar and ended 1320 ft, a quarter mile, upstream. Once the geofenced region was defined, the events that occurred within those regions were selected, and the GPS location of each event was compared to the location of the stop bar in order to calculate the distance from stop bar. Figure 5.1a shows the hard-braking events for an intersection along the study corridor. Figure 5.1b shows the upstream geofence regions and the geofenced hard-braking events color coded by speed. The 400 ft boundary, relative to the stop bar, roughly corresponds to the location of the dilemma zone detectors at this intersection (Gazis et al., 1960; Hunter, Saldivar-Carranza, et al., 2021; Parsonson, 1978; Zegeer & Deen, 1978).



(a) Approximately 3,000 hard-braking event points around the intersection of SR 37 and #4 Southport Rd.



(b) Approximately 1,600 hard-braking points captured by the north and southbound upstream geofence regions. Hard-braking event points are colorized by speed of vehicle at the time of the event.

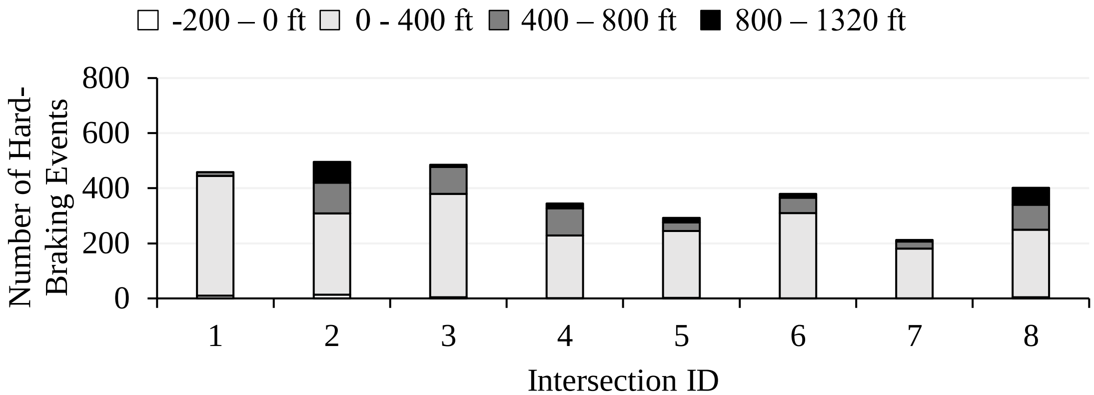
Figure 5.1. Visualization of event processing (Hunter, Saldivar-Carranza, et al., 2021)

5.3 Hard-Braking

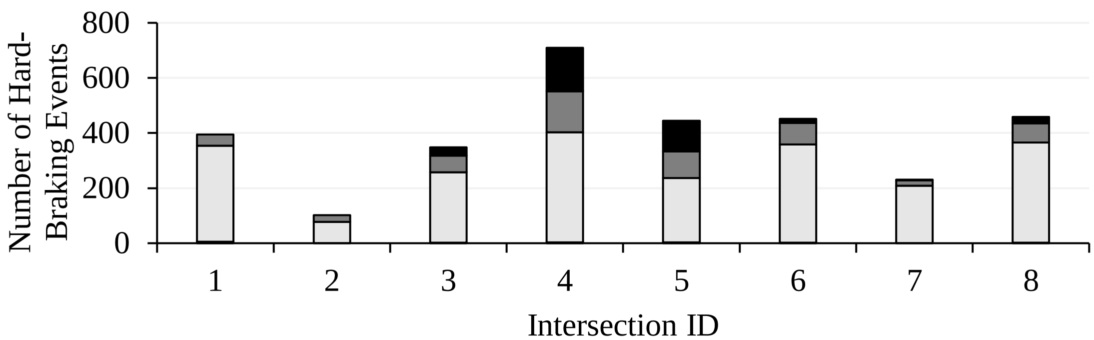
5.3.1 Analysis: Hard-Braking Events by Distance

The hard-braking events are classified by their distance from the stop bar to study the impact of dilemma zone (Gazis et al., 1960; Parsonson, 1978; Zegeer & Deen, 1978) and queuing. Type II dilemma zone has been defined in previous literature as the road segment where there is a 10% - 90% probability of a vehicle stopping at the beginning of the yellow light (Parsonson, 1978). The occurrence of hard-braking events less than 400 ft (location of advance detector upstream of stop bar at 55 MPH speed limit zone) from the stop bar at lower speeds are possibly due to vehicles stopping for the red light, whereas such occurrences at higher speeds could be due to dilemma zone issues. Hard-braking events occurring at distances greater than 400 ft from the stop bar are potentially due to long queues during oversaturated conditions.

Figure 5.2 shows the number of weekday hard-braking events occurring at each intersection, stacked by distance from the stop bar, aggregated over the month of July 2019. For both northbound and southbound approaches, the majority of the hard-braking events occur within 400 ft of the stop bar (73%). However, there are a few intersections (#8 Smith Valley Rd., in NB and #4 Southport Rd. and #5, Wicker Rd. in SB) where more than 40% of hard-braking events occurred more than 400 ft from the stop bar (Hunter, Saldivar-Carranza, et al., 2021). Additionally, comparing the number of trajectories to pass through each intersection in the northbound and southbound directions (Figure 3.2a and Figure 3.2b) and the number of hard-braking events by intersection reveals that the number of hard-braking events is not directly related to the number of trajectories of the same direction. However, there may be a positive relationship between the number of trajectories to pass through each intersection in the eastbound and westbound directions (Figure 3.2c and Figure 3.2d) and the number of hard-braking events by intersection. For example, southbound intersection 4, Southport Rd., has the most hard-braking events but is far from having the most trajectories in the northbound or southbound directions. However, southbound intersection 4, Southport Rd., does have the greatest number of cross street trajectories.



(a) Northbound



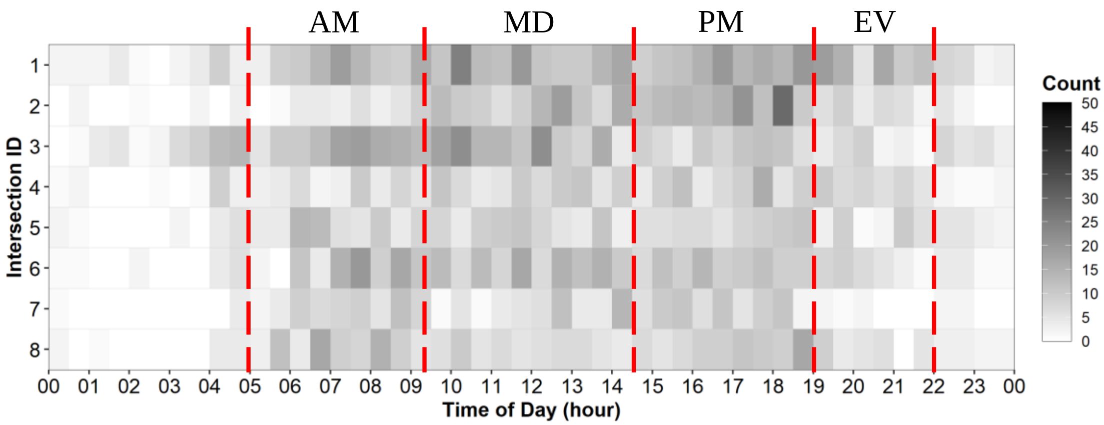
(b) Southbound

Note: Stop bar is located at 0 ft.

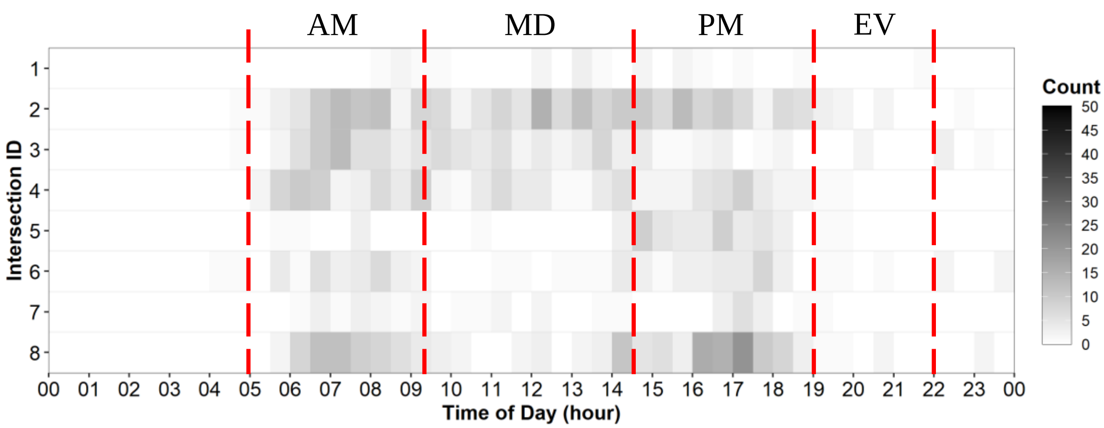
Figure 5.2. Number of weekday hard-braking events by intersection and distance from stop bar

To understand the temporal nature of the hard-braking events and their distances from the stop bar, a heatmap was generated. Figure 5.3 illustrates a heatmap of the number of hard-braking events, during weekdays in July 2019, on the northbound approach over a 24-hour period (30-minute bins) across two distance categories – less than 400 ft and greater than 400 ft. For the less than 400 ft category, the majority of hard-braking events occur during the AM, MD and PM plans (Figure 5.3a), with no clear pattern or trend. For the 400 – 1320 ft range (Figure 5.3b), there are generally fewer hard-braking events, except for perhaps intersection 8, Smith Valley Rd, during the PM plan.

Figure 5.4 shows a heatmap similar to Figure 5.3**,** for the southbound approach. Hard-braking events within 400 ft of the intersection (Figure 5.4a) are generally higher for the PM plan, especially at intersection 8, Smith Valley Rd. Figure 5.4b, which is comprised of events occurring beyond 400 ft, shows a different pattern than the northbound approaches. Intersection 4, Southport Rd., and intersection 5, Wicker Rd., experience a large number of hard-braking events during the PM plan. This could be indicative of hard-braking events that occur at the back of long queues during the PM peak period (Hunter, Saldivar-Carranza, et al., 2021).

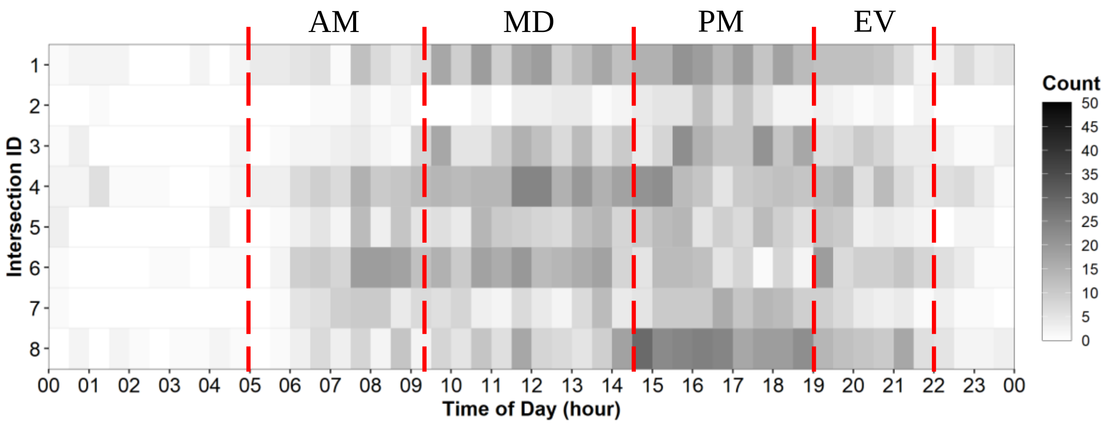


(a) Between 0 and 400 ft upstream of the stop bar

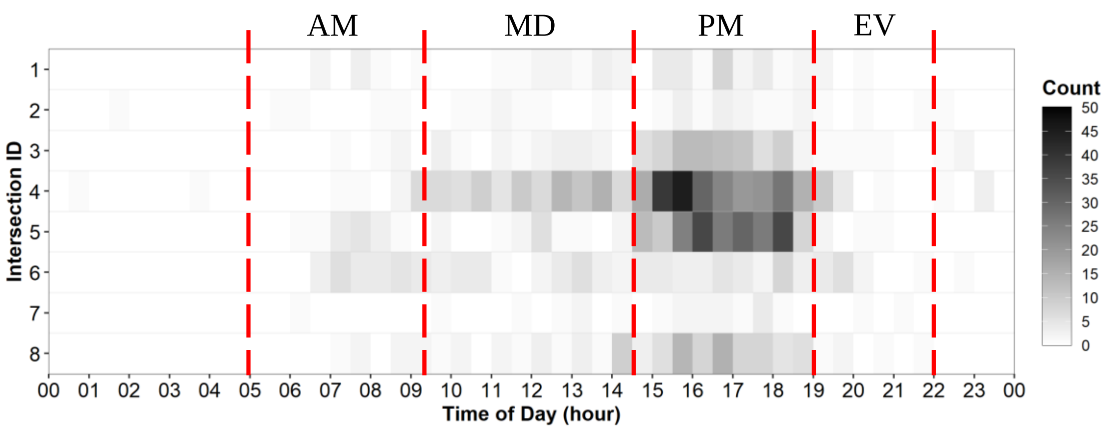


(b) Greater than 400 ft upstream of the stop bar

Figure 5.3. Heatmap of weekday hard-braking events by intersection for northbound SR-37, in July 2019



(a) Less than 400 ft from stop bar



(b) Greater than 400 ft from stop bar

Figure 5.4. Heatmap of weekday hard-braking events by intersection for southbound SR-37, in July 2019

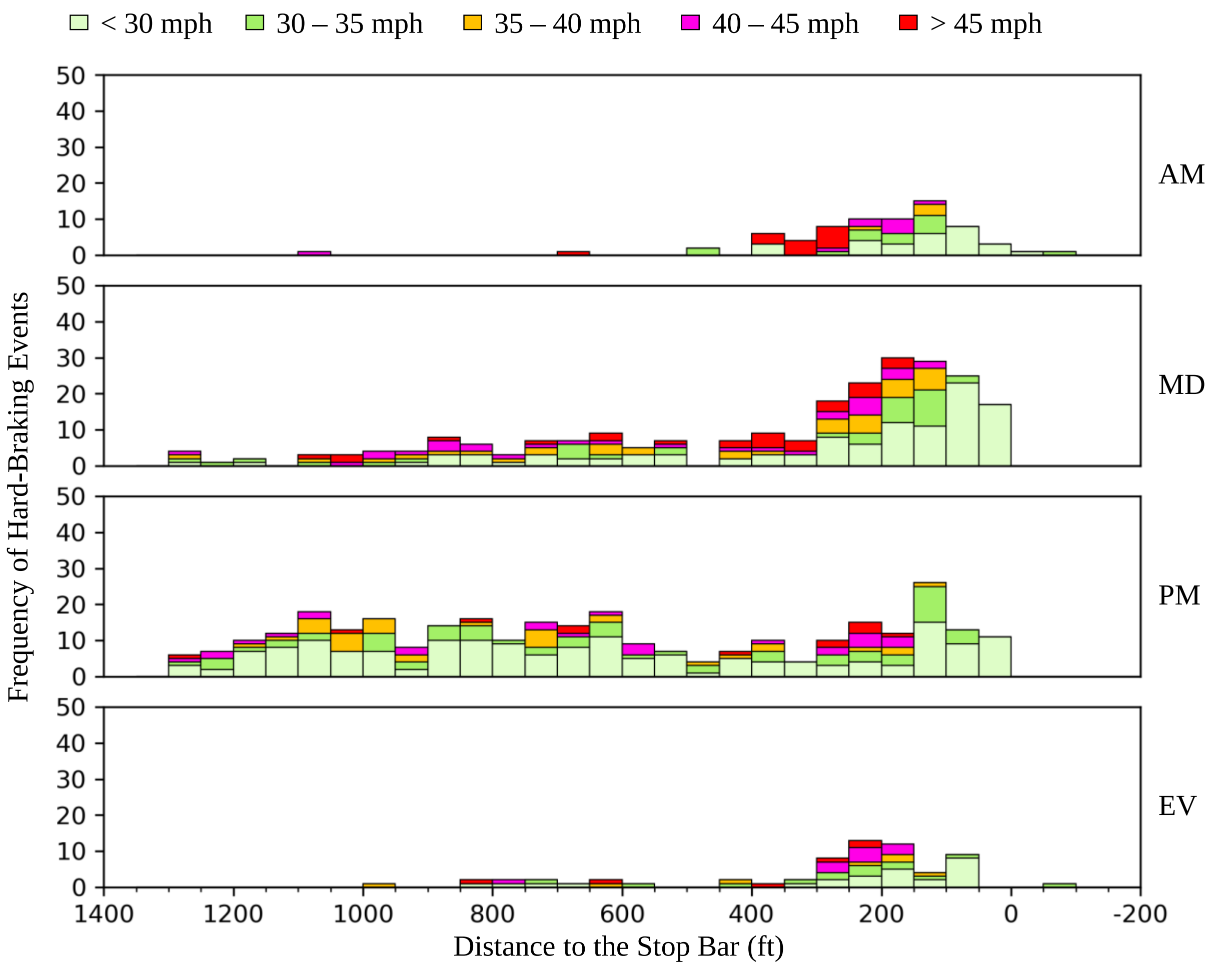
5.3.2 Analysis: Hard-Braking Pattern by Intersection

To further investigate the pattern of hard-braking events, a histogram of the events stacked by speeds were plotted for different time of day plans over their distance from the stop bar. Figure 5.5 and Figure 5.6 present two such patterns for weekdays between 5:00 AM and 10:00 PM in July 2019.

Figure 5.5 shows the hard-braking events at the southbound approach of intersection 4, Southport Rd. During the PM time plan (Figure 5.5b), hard-braking events are occurring consistently for the entirety of the quarter-mile from the stop bar, with very few of those hard-braking events occurring at speeds over 45 mph. The aerial image in Figure 5.5a shows that there are no driveways or bus stops in the region that could be contributing to these hard-braking events.

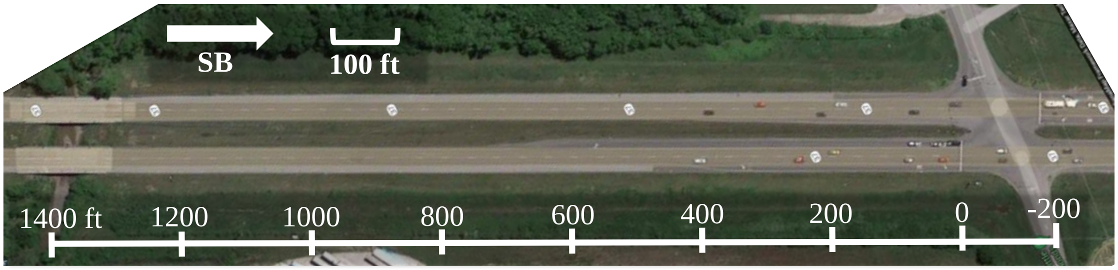
Figure 5.6 shows the hard-braking events at the southbound approach of intersection 8, Smith Valley Rd. The PM plan, (Figure 5.6b), stands out as having numerous hard-braking events within the 0 – 400 ft region. In some of the speed bins around 250 ft upstream of the intersection, over 60% of those hard-braking events occur at speeds above 45 mph which could indicate dilemma zone issues. Dilemma zone protection is often difficult on coordinated movements as more phases compete for green time and coordinated phases are forced off (Hunter, Saldivar-Carranza, et al., 2021).

(a) Aerial photo of the southbound approach

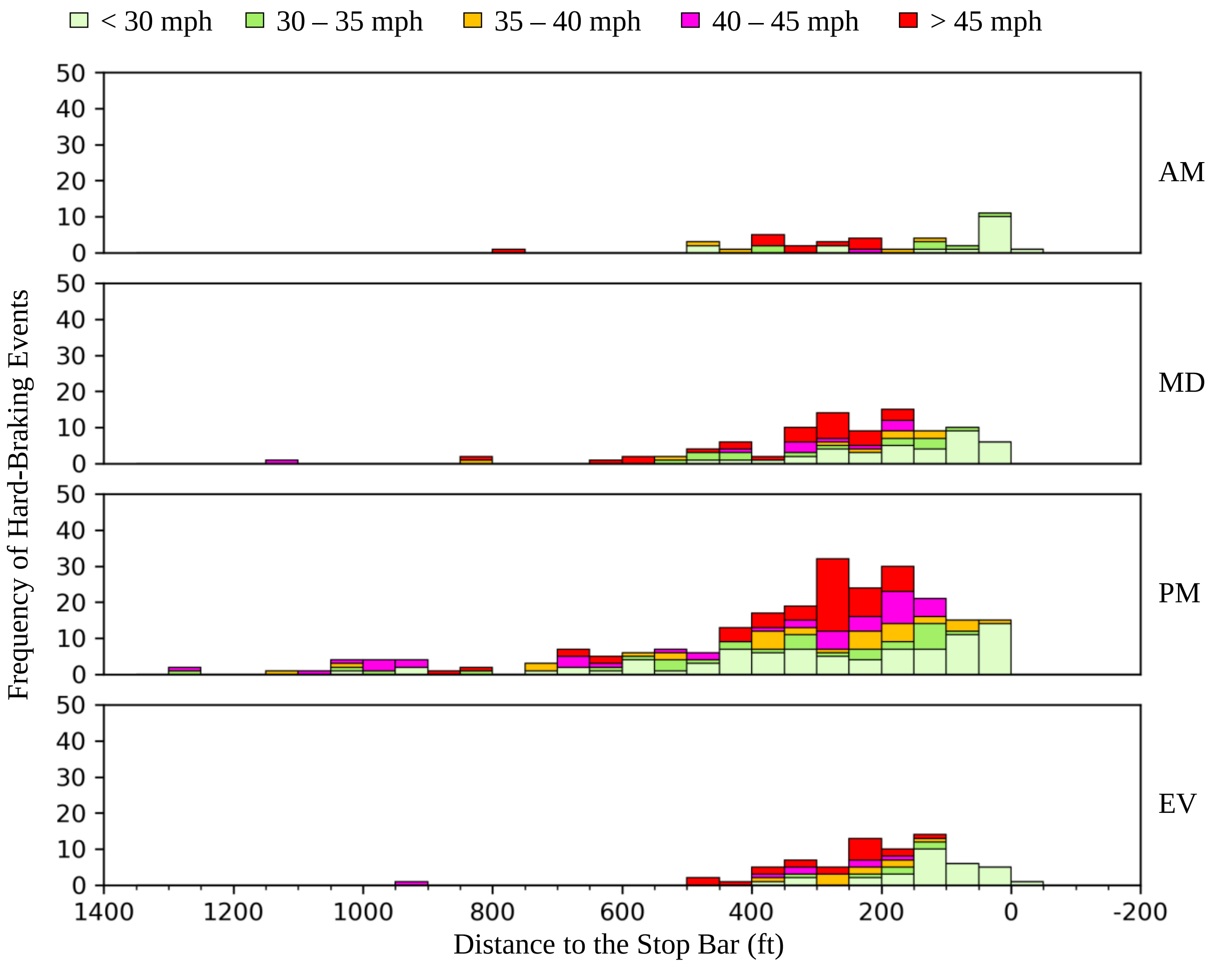


(b) Frequency of hard-braking events by distance to the stop bar and speed for weekdays, July 2019

Figure 5.5. Southbound approach, SR-37 at Southport Road (Intersection 4)



(a) Aerial photo of the southbound approach



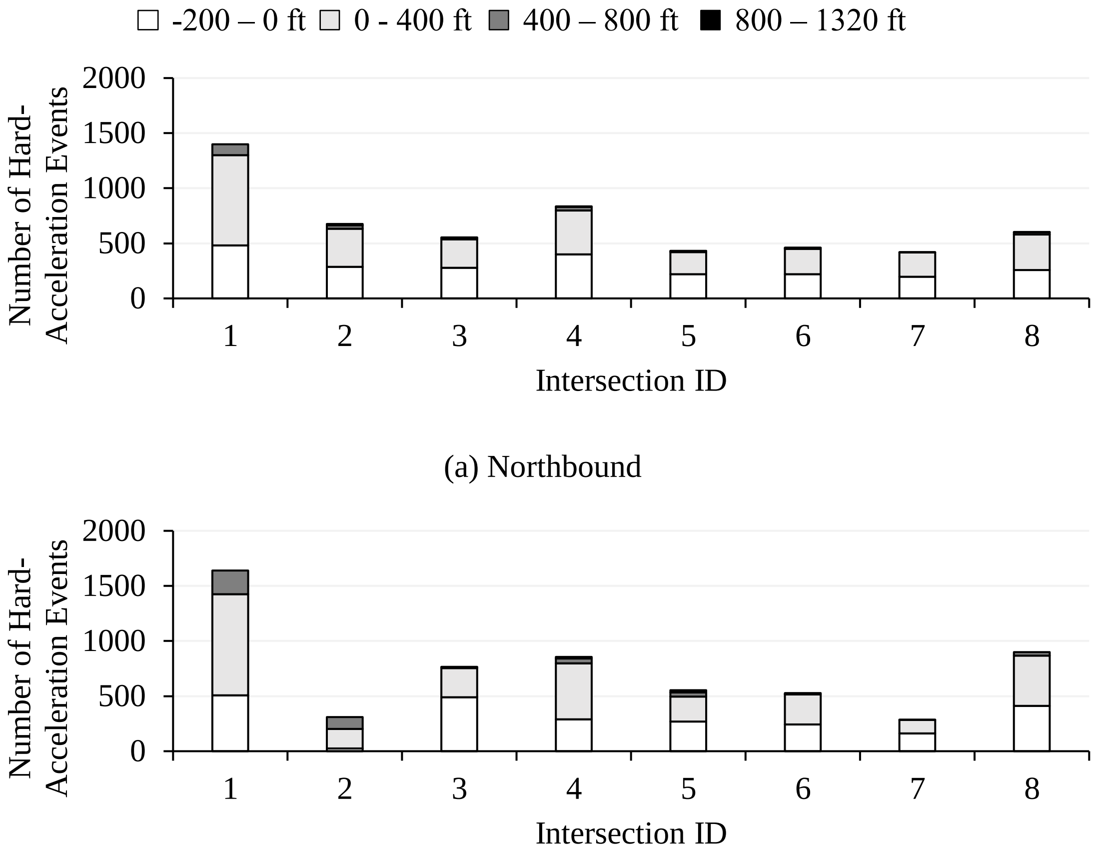
(b) Frequency of hard-braking events by distance to the stop bar and speed for weekdays, July 2019

Figure 5.6. Southbound approach, SR-37 at Smith Valley Road (Intersection 9)

5.4 Hard-Acceleration

5.4.1 Analysis: Hard-Acceleration by Distance

As with hard-braking, the hard-acceleration events are first classified by their distance from the stop bar. Figure 5.7 shows the number of weekday hard-acceleration events occurring at each intersection, stacked by distance from the stop bar, aggerated over July 2019. Similar to hard-braking, a large portion of hard-acceleration events occurred between the stop bar and 400 ft upstream (51%). However, while a negligible number of hard-braking events occurred downstream of the stop bar, over 40% of hard-acceleration events occurred past the stop bar. Additionally, a disproportionate number of hard-acceleration events, almost 30%, occurred at intersection 1, Thompson Rd. Like hard-braking, the number of hard-acceleration events did not directly trend with the number of trajectories traveling in the northbound and southbound directions (Figure 3.2a and Figure 3.2b). However, unlike hard-braking, no discernable pattern is apparent between the number of hard-acceleration events and the number of trajectories in the eastbound and westbound directions (Figure 3.2c and Figure 3.2d) either.



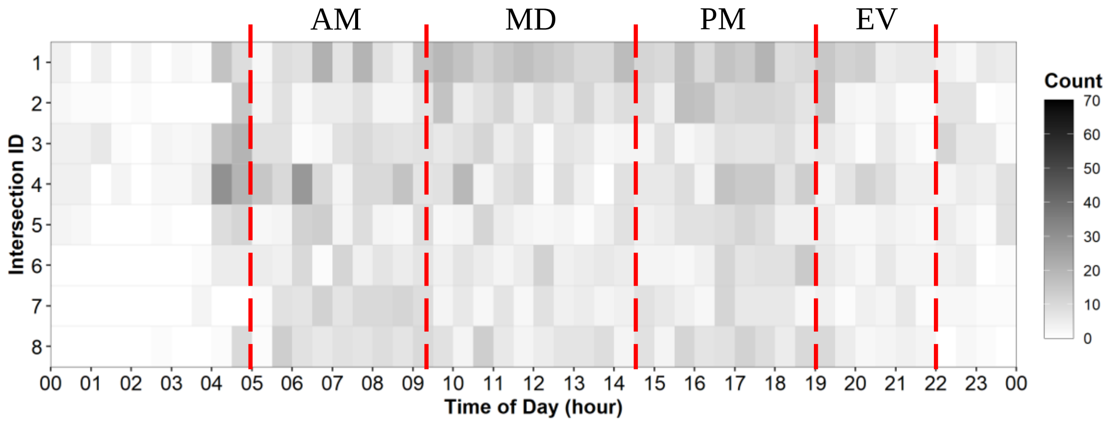
(a) Northbound

(b) Southbound

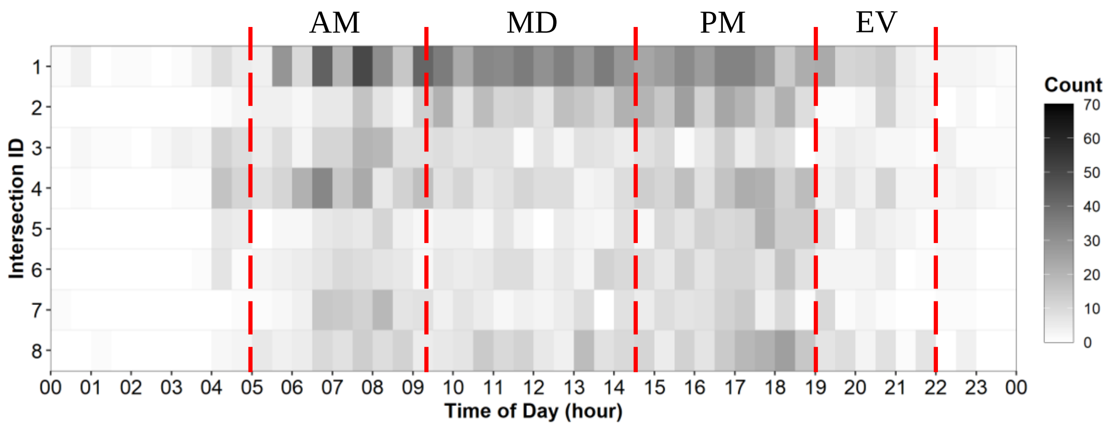
Note: Stop bar is located at 0 ft.

Figure 5.7. Number of weekday hard-acceleration events by intersection and distance from stop bar

Temporal heatmaps were also generated for hard-acceleration events. While the hard-braking heatmaps focused on the specific location of the even upstream of the stop bar, these hard-acceleration heatmaps are divided by events occurring downstream of the stop bar (-200 – 0 from the stop bar) and upstream of the stop bar (0 – 1320 ft from stop bar). Figure 5.8 and Figure 5.9 show the number of hard-acceleration events, during weekdays in July 2019, for the northbound and southbound approaches, respectfully. In the northbound direction, no pattern stands out in the downstream region (Figure 5.8a); however, in the upstream region, intersection 1, Thompson Rd., stands out has having more hard-acceleration events than other intersections throughout the daylight hours (Figure 5.8b). In the southbound direction, the downstream region, as with the northbound direction, has no major discernable pattern (Figure 5.9a). Upstream of the stop bar in the southbound direction, however, has a clustering of hard-acceleration events in the PM time period at intersection 1, Thompson Rd., intersection 4, Southport Rd., intersection 5, Wicker Rd., and intersection 8, Smith Valley Rd. (Figure 5.9b).

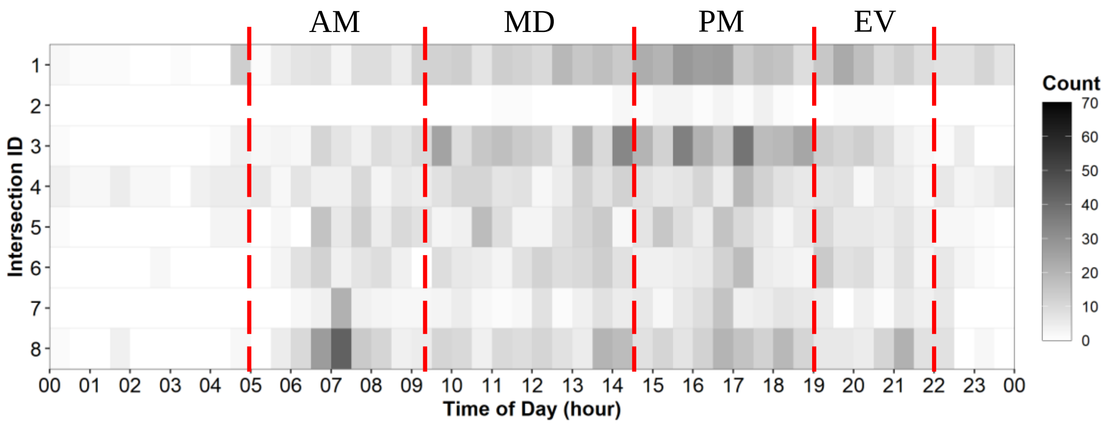


(a) Downstream of the stop bar

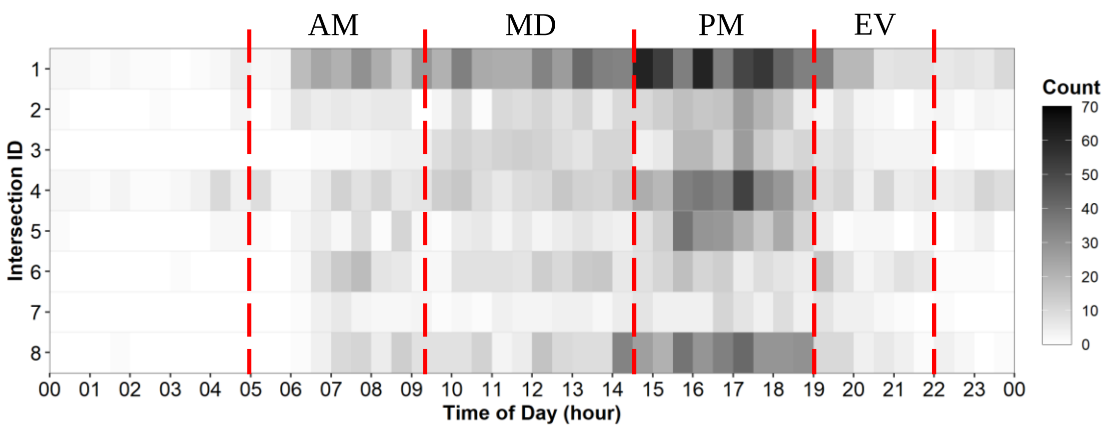


(b) Upstream of the stop bar

Figure 5.8. Heatmap of weekday hard-acceleration events by intersection for northbound SR-37, in July 2019



(a) Downstream of the stop bar



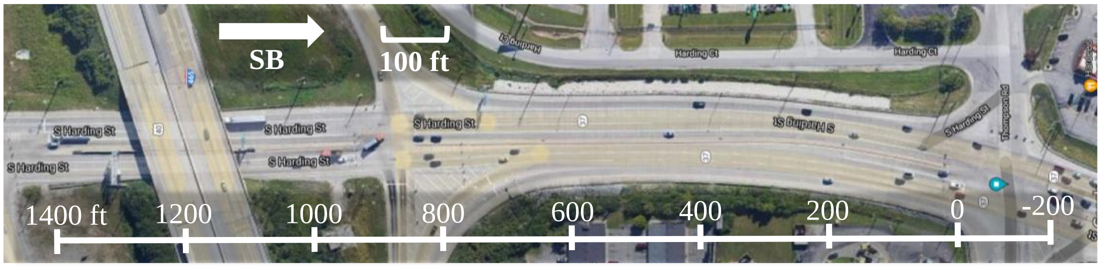
(b) Upstream of the stop bar

Figure 5.9. Heatmap of weekday hard-acceleration events by intersection for southbound SR-37, in July 2019

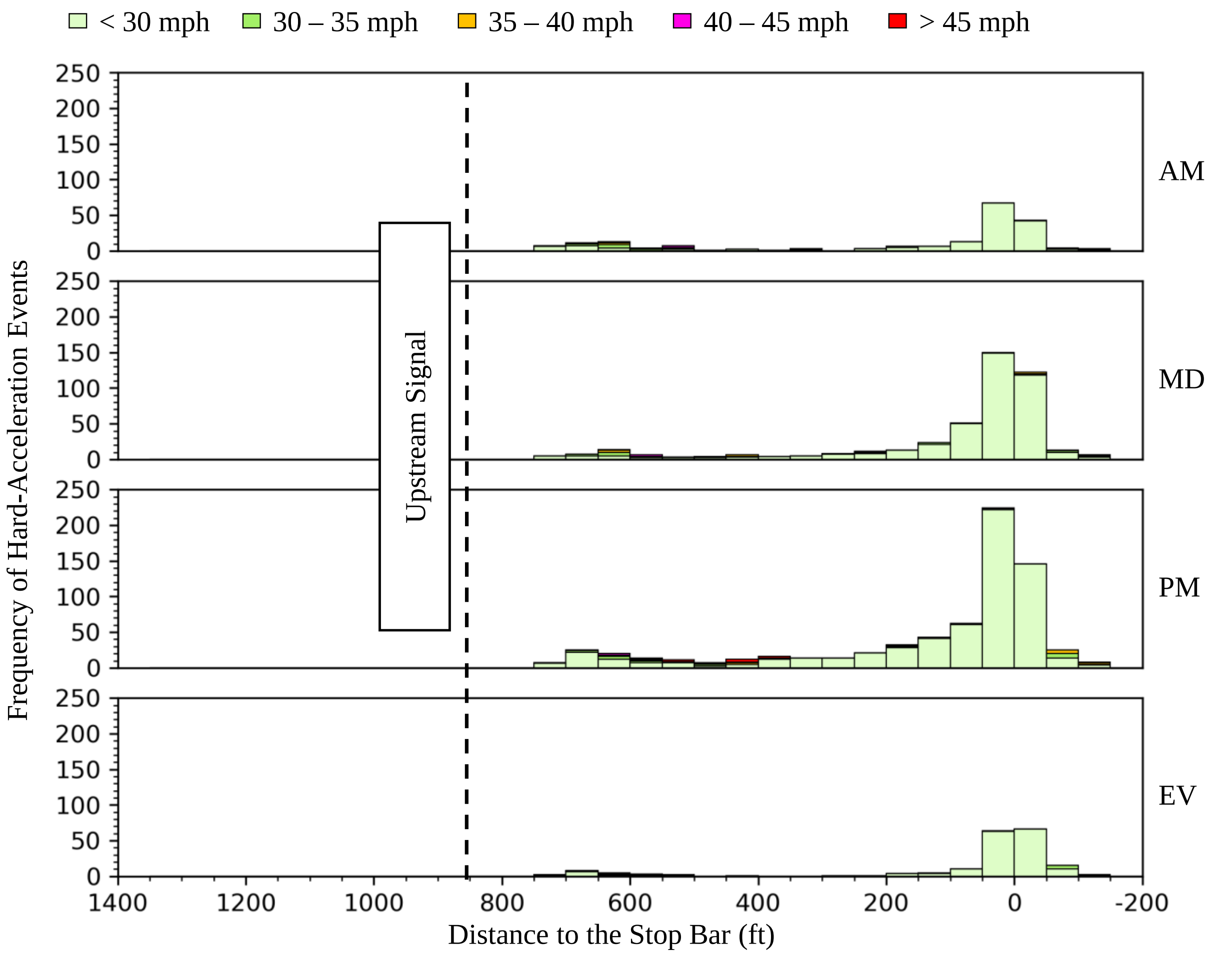
5.4.2 Analysis: Hard-Acceleration Pattern by Intersection

Further replicating the hard-braking study with hard-acceleration, histograms of events stacked by speeds, plotted for different time of day plans, over their distance from the stop bar were created. Figure 5.10 shows an example of these plots.

Figure 5.10 shows the hard-acceleration event pattern for the southbound approach of intersection 1, Thompson Rd. Perhaps, unsurprisingly, the majority of hard-acceleration events regardless of time of day occur just before the stop bar or just after the stop bar (Figure 5.10b). Additionally, the vast majority of these events are occurring at speeds less than 30 mph. This could indicate that vehicles are rapidly accelerating as the signal turns to yellow or even red which could further indicate a dilemma zone issue and/ or an eagerness to accelerate after the light has turned green.



(a) Aerial photo of the southbound approach



(b) Frequency of hard-acceleration events by distance to the stop bar and speed for weekdays, July 2019

Figure 5.10. Southbound approach, SR-37, at Thompson Road (Intersection 1)

6. CORRELATION: EVENT DATA AND CRASHES

6.1 Hard-Braking and Rear-End Collisions: 30 Minute Bins

In addition to the graphical visualizations highlighting similar patterns between crashes and events, several correlation tests are performed to determine if a linear correlation is present. In the first correlation test, the aggregated July 2019 weekday hard-braking events occurring over a 30-minute period are compared with the aggregated 4.5-year period rear-end crashes occurring over the same 30-minute period (Hunter, Saldivar-Carranza, et al., 2021). Rear-end collisions were the focus of this first correlation test due to the fact that the vast majority of collisions at intersections along this corridor were rear-end collisions. Additionally, hard-braking and rear-end collisions are intuitively related; A common reaction to approaching a vehicle and sensing a collision is to slam on the brakes.

6.1.1 Correlation Test

A simple Spearman rank order correlation test (Spearman, 1904) is conducted to evaluate the monotonic relationship between a pair of data. The correlation coefficient, r_s, represents the strength of that relationship. There are many interpretations in the literature (C.P & J., 2007; Y.H., 2003) on coefficient thresholds, but this study utilizes a conservative interpretation suggested by Evans (Evans, 1996) as seen in Table 6.1.

Table 6.1. Spearman: Interpretation of Correlation Coefficient

Correlation Coefficient	Correlation Significance
0.80 – 1.0	Very Strong
0.60 – 0.79	Strong
0.40 – 0.59	Moderate
0.20 – 0.39	Weak
0.00 - 0.19	Very Weak

Table 6.2 and Table 6.3 show the results of the Spearman test conducted at 95% and 99% confidence levels and highlights intersections with a strong correlation, for northbound and southbound respectively. Results indicate a strong correlation between rear-end crashes and hard-braking events past 400 ft of the stop bar at northbound intersection 8, Smith Valley Rd., and

southbound intersection 4, Southport Rd., and intersection 5, Wicker Rd. A check in the strong correlation box is used if the r_s value exceeds the 0.6 threshold shown in Table 6.1.

Interestingly, while southbound intersection 8, Smith Valley Rd. experienced a high number of high-speed hard-braking events within 250 ft of the stop bar (Figure 5.6b), this location does not exhibit a strong correlation to rear-end crashes as suggested by prior conflict models (Hunter, Saldivar-Carranza, et al., 2021; Sharma et al., 2011).

Table 6.2. Spearman's correlation between intersection rear-end crash counts and number of hard-braking events by distance, for northbound SR-37

Int ID	0 – 400 ft			400 – 1320 ft		
	r_s	p-value	Strong Correlation	r_s	p-value	Strong Correlation
1	0.23	0.11		0.21	0.15	
2	0.10	0.52		0.44*	0.002	
3	0.25	0.09		0.33**	0.02	
4	0.16	0.28		0.28	0.06	
5	-0.15	0.31		0.33**	0.02	
6	0.20	0.18		0.2	0.19	
7	0.34**	0.02		0.15	0.32	
8	0.42*	<0.001		0.65*	<0.001	✓

** Significant at 99% Confidence Level*

*** Significant at 95% Confidence Level*

Table 6.3. Spearman's correlation between intersection rear-end crash counts and number of hard-braking events by distance for southbound SR-37

Int ID	0 – 400 ft			400 – 1320 ft		
	r_s	p-value	Strong Correlation	r_s	p-value	Strong Correlation
1	0.54*	<0.001		0.15	0.32	
2	0.15	0.3		0.08	0.58	
3	0.55*	<0.001		0.57*	<0.001	
4	0.53*	<0.001		0.72*	<0.001	✓
5	0.44*	0.002		0.61*	<0.001	✓
6	0.46*	0.001		0.31**	0.03	
7	0.12	0.14		0.22	0.13	
8	0.33**	0.022		0.23	0.11	

** Significant at 99% Confidence Level*

*** Significant at 95% Confidence Level*

6.1.2 Sensitivity Analysis

To determine if one month of hard-braking event data is sufficient to suggest a reasonable correlation between hard-braking events and crashes, a sensitivity analysis using Spearman's correlation is performed. While this study primarily uses one month of hard-braking data collected from July 2019, the sensitivity analysis includes data from July and August 2019. Figure 6.1 shows the results of this analysis. The two plots in Figure 6.1 show that the r_s values plateaus around 4 weeks' worth of data. This suggests that one month of hard-braking data is sufficient to result in a reliable correlation with over 4.5 years' worth of crash data (Hunter, Saldivar-Carranza, et al., 2021).

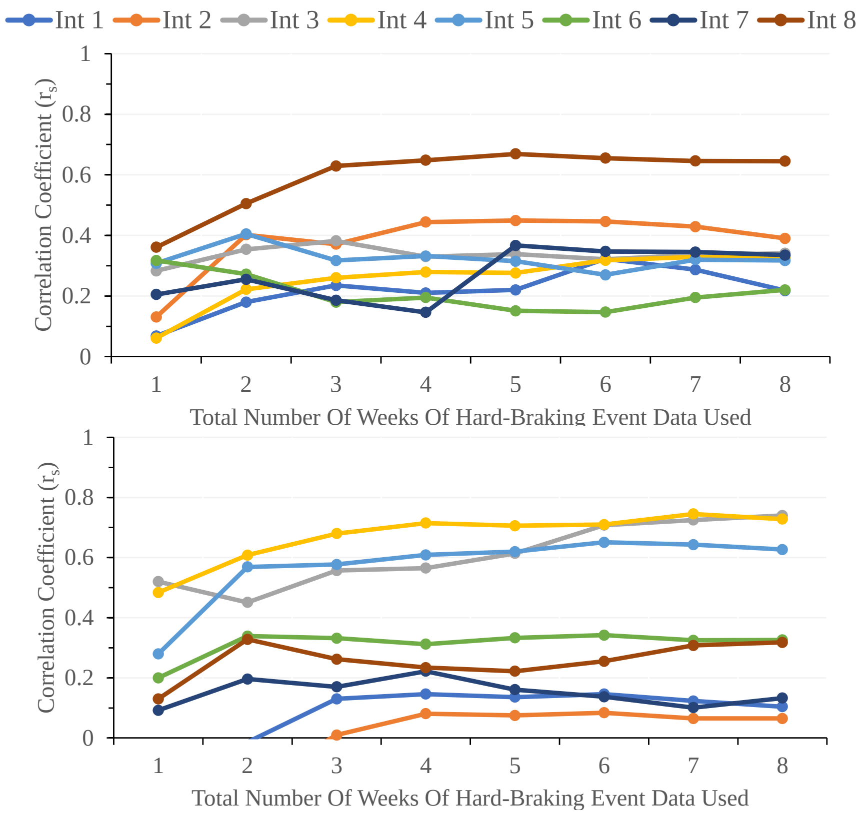


Figure 6.1. Sensitivity analysis for Spearman correlation between hard-braking events and rear-end crashes for 8 weeks in July and August 2019

6.2 Event Data and Collisions: A Better Fit

Next, the study compared different time bins, types of crashes, and the relationship between hard-acceleration and crashes to determine if a better correlation could be achieved. Table 6.4 and Table 6.5 show the results of this comparison. Table 6.4 presents the number of intersections to have a strong or very strong correlation between hard-braking and all collisions and specifically rear-end collisions for both directions and three distance regions: 0 – 400 ft, 400 – 1320 ft, and 0 – 1320 ft. Overall, binning hard-braking and crashes in 3-hour time bins was the most affective in achieving a strong or very strong correlation between collisions and hard-braking events. In the southbound direction, in the 3-hour time bin, all 8 intersections had a strong or very strong correlation between rear-end collisions and hard-braking events occurring in the 0-1320 ft region.

Table 6.4. Number of intersections to have a strong or very strong correlation between hard-braking events and collisions for different time bins

	NB					SB				
	15 Min	**30 Min**	**1 Hour**	**2 Hour**	**3 Hour**	**15 Min**	**30 Min**	**1 Hour**	**2 Hour**	**3 Hour**
0 – 400 ft										
All	0	0	0	1	5	0	0	3	4	5
Rear–End	0	0	1	2	4	0	0	4	4	7
400 – 1320 ft										
All	0	0	0	5	5	0	2	5	5	6
Rear–End	0	1	1	4	6	0	2	4	5	6
0 – 1320 ft										
All	0	0	1	3	6	0	1	5	5	7
Rear–End	0	0	1	4	5	0	1	5	5	8

Note: Max value is 8 intersections

Table 6.5 shows the number of intersections to have a strong or very strong correlation between hard-acceleration and all collisions, specifically rear-end collisions, and specifically right-angle collisions. Right-angle collisions were added to the hard-acceleration analysis because it was speculated that vehicles rapidly accelerating to cross the intersection before the red signal would be in direct conflict with cross street traffic. For this same reason, an additional distance range, -200 – 0 ft, was included in order to capture hard-acceleration events occurring after the stop bar. Like hard-braking, the 3-hour time bin was the most effective in correlating hard-acceleration to crashes. Additionally, like hard-braking, in the southbound direction, in the 3-hour time bin, all 8 intersections had a strong or very strong correlation between rear-end collisions and hard-acceleration events occurring in the 0-1320 ft region. Interestingly, the distance range where right-angle collisions are most likely to occur, -200 – 0 ft, had the least number of intersections with a strong or very strong correlation between right-angle collisions and hard-acceleration events.

Table 6.5. Number of intersections to have a strong or very strong correlation between hard-acceleration events and collisions for different time bins

	NB					SB				
	15 Min	**30 Min**	**1 Hour**	**2 Hour**	**3 Hour**	**15 Min**	**30 Min**	**1 Hour**	**2 Hour**	**3 Hour**
-200 – 0 ft										
All	0	0	0	3	3	0	1	4	4	6
Rear – End	0	0	0	2	3	0	0	3	3	6
Right–Angle	0	0	0	0	1	0	0	0	0	1
0 – 400 ft										
All	0	0	1	4	4	0	1	4	4	6
Rear – End	0	0	1	3	2	0	0	5	4	7
Right–Angle	0	0	0	1	5	0	0	3	4	5
400 – 1320 ft										
All Collisions	0	0	0	3	3	0	2	3	3	4
Rear – End	0	0	1	3	3	0	2	3	3	5
Right–Angle	0	0	0	5	5	0	2	5	5	6
0 – 1320 ft										
All Collisions	0	0	1	3	5	0	1	4	4	7
Rear – End	0	0	0	4	3	0	1	4	4	8
Right–Angle	0	0	1	3	6	0	1	5	5	7

Note: Max value is 8 intersections

Due to there being 4 million more hard-acceleration events in Indiana than hard-braking events in July 2019, it was hypothesized that hard-acceleration would be a better predictor of crashes than hard-braking. However, in this study, this was not true. In the 0 – 1320 ft region across all time bins for all collisions and rear-end collisions, hard-acceleration had 49 strong / very strong correlations, while hard-braking had 57. Likewise, in the 400 – 1320 ft region, hard-acceleration had 38 strong / very strong correlations, while hard-braking had 57. The only range where hard-acceleration had more strong / very strong correlations was the 0 – 400 ft region. In this region across all time bins for all collisions and rear-end collisions, hard-acceleration had 46 strong / very strong correlations while hard-braking had 40.

6.3 Volume Correlation

Finally, to understand the relationship between traffic volume and crashes, hard-braking, and hard-acceleration, a Spearman's rank order correlation test was performed. The volume data was collected from imbedded loop detectors for 3 weekdays in July 2019 and then averaged to estimate intersection volume. Table 6.6 shows the results of this analysis for 4 different time bins. The correlation between volume and crashes increased as the time bins increased, while both hard-braking and hard-acceleration remained strongly to very strongly correlated with volume for all time bins. The strong correlation between hard-braking and hard-acceleration may not be surprising but suggests it can be a powerful tool for assessing intersections with potential safety issues without waiting for crash data. Intersections with a disproportionate amount of hard-braking / hard-acceleration events could be a strong indicator that the intersection needs to be evaluated further.

Table 6.6. Spearman's correlation between volume and crashes, hard-braking, and hard-acceleration for multiple time bins

	30 min	**1 Hour**	**2 Hour**	**3 Hour**
Crashes	0.38	0.48	0.56	0.63
Hard-braking	0.72	0.74	0.76	0.74
Hard-acceleration	0.79	0.82	0.83	0.83

7. DATA REPRESENTATIVENESS

7.1 The Big Question

Connected vehicle data is opening new frontiers for agencies to evaluate the performance of their road networks. In addition to hard-braking and hard-acceleration, the resulting data sets also have the capabilities of providing agencies with a rich set of data, such as traffic signal performance measures, interstate congestion, and common detours around road closures (Desai et al., 2020a; Hunter, Saldivar-Carranza, et al., 2021; McNamara et al., 2015; E. Saldivar-Carranza et al., 2020).

However, many agencies are concerned about the representativeness of the data. In fact, the lack of any systematic evaluation of regional variation in penetration is perhaps the biggest barrier to widespread use of connected vehicle data by transportation agencies. This chapter presents a methodology for calculating connected vehicle percent penetration using two data sets: Department of Transportation (DOT) collected traffic count data and connected vehicle (CV) trajectory data. This chapter reports the observed penetration of connected vehicles observed adjacent to selected count stations in the states of California (CA), Connecticut (CT), Georgia (GA), Indiana (IN), Minnesota (MN), North Carolina (NC), Ohio (OH), Pennsylvania (PA), Texas (TX), Utah (UT), and Wisconsin (WI).

The organization of this chapter begins by discussing the locations and data used in this study, and then, explains the methodology used to calculate the hourly, daily, and monthly percent penetration for each station. Next, section 6.4 Aggregate Results discusses the percent penetration Indiana and for all 11 states aggregated over all applicable stations. Finally, section 6.5 Disaggregate Results delves into individual stations. Four example outlier stations are explored in depth to provide further understanding behind how the percent penetrations are calculated and to understand potential reasons for the stations' outlying percent penetration.

7.2 Data

For this study, 381 continuous count stations were selected to be geographically distributed, represent both interstate and non-interstate roadways, have a variety of traffic volumes, and to be in both rural and urban environments (Figure 7.1).

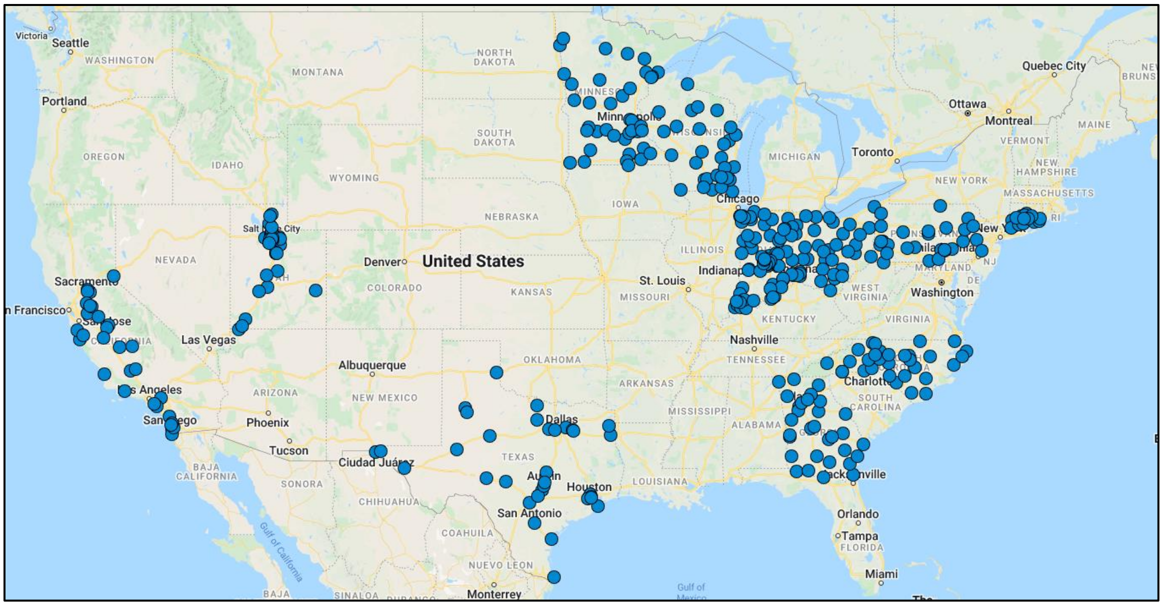


Figure 7.1. Locations of DOT count stations used in this study

Table 7.1 provides information on the number of count stations divided by interstate, non-interstate, rural, and urban. Not every count station has data available for every hour, day, or month; therefore, Table 7.1 also differentiates between the number of count stations used in August 2020 and August 2021. While overall 381 count stations were used in this study, only 343 stations reported data in August 2020 and 349 stations reported in August 2021. There were 315 count stations that reported data both in August 2020 and August 2021.

Table 7.1. Count Station Attributes

State	Interstate	Non-Interstate	Rural	Urban		Total
August 2020						
CA	11	18	9	20		29
CT	10	6	5	11		16
GA	16	15	17	14		31
IN	24	32	34	22		56
MN	12	23	27	8		35
NC	13	10	14	9		23
OH	24	13	18	19		37
PA	14	12	13	13		26
TX	19	13	14	18		32
UT	16	11	6	21		27
WI	18	13	21	10		31
Aug 2020 Total	177	166	178	165		343
August 2021						
CA	9	19	10	18		28
CT	9	6	5	10		15
GA	16	15	17	14		31
IN	34	29	35	28		63
MN	12	21	24	9		34
NC	19	12	18	13		31
OH	20	13	17	16		33
PA	15	11	13	13		26
TX	18	11	14	15		30
UT	18	13	9	22		33
WI	17	12	20	9		30
Aug 2021 Total	187	162	182	167		349

The traffic counts for the 381 count stations were obtained from their respective state DOTs and are, for the purposes of this study, considered the ground truth vehicle counts. Many different technologies are utilized at continuous count stations, such as inductive loops, piezoelectric sensors, and magnetic sensors (Federal Highway Administration, 2016). An example count station, located on I-70 in Indiana, utilizes inductive loops, as shown in Figure 7.2, and the location of inductive loop sensors is identified with callout i.

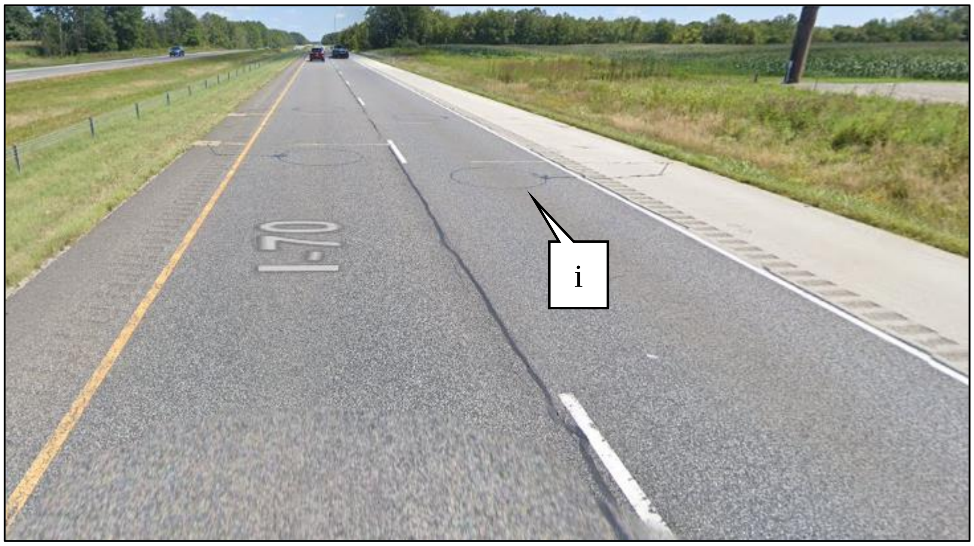


Figure 7.2. Inductive loops (i) at Indiana station 950106 (I-70 MM 25.8)

7.2.1 DOT Traffic Count Data

The majority of the traffic volume data (aggregated by hour) used in this study are publicly available online. However, some data was collected via correspondence with the DOT. The following list details how the DOT counts were collected. Additional details for each state's analysis are provided in Appendix A.

- CA: Performance Measurement System (Caltrans, n.d.)
- CT: Provided via email
- GA: Traffic Analysis and Data Application (GDOT & Drakewell, n.d.)
- IN: Traffic Count Database System (INDOT & MS2, n.d.)
- MN: Traffic Forecasting and Analysis Data Products (MnDOT, n.d.)
- NC: Traffic Data Management System (NCDOT & MS2, n.d.)
- OH: Traffic Monitoring Management System (ODOT & MS2, n.d.)
- PA: Traffic Information Repository (PennDOT, n.d.)
- TX: Traffic Count Database System (TXDOT & MS2, n.d.)
- UT: Performance Measurement System (Iteris & UDOT, n.d.)
- WI: Provided via email

7.2.2 Vehicle Trajectory Data

The vehicle trajectory data used in this chapter consists of anonymized individual waypoints that are collected every three seconds along with an anonymized trajectory identifier and GPS, timestamp, and heading information. This data was obtained through a third-party provider. This provider receives its data directly from the original equipment manufacturers (OEMs).

The vehicle trajectory counts were obtained by identifying quarter mile geofence regions near the count station that spanned the entire width of the road. In some cases, due to intersections, driveways, or curves in the road, the geofence region was shortened to avoid these features. The vehicle trajectory waypoints located inside the geofence region were selected, and the number of unique trajectories were counted. To account for trip chaining, if a trajectory identifier appeared more than 10 minutes apart or in the opposite direction, it was counted as an additional trip (Hunter, Mathew, Cox, et al., 2021; Hunter, Mathew, Li, et al., 2021).

7.3 Methodology

62 days across August 2020 and August 2021 were analyzed for 11 states (CA, CT, GA, IN, MN, NC, OH, PA, TX, UT, and WI). In addition, a longer longitudinal analysis for Indiana was conducted for the following months: July 2019, January 2020, June 2020, July 2020, September 2020, April 2021, May 2021, June 2021, July 2021, September 2021, October 2021, January 2022, and February 2022.

To calculate the hourly percent penetration, the DOT and vehicle trajectory counts were aggregated by hour. This was calculated by

$$H_p = \left(\frac{V_h}{C_h}\right)100 \qquad \text{Eq. 1}$$

where H_p is the hourly percent penetration, V_h is the hourly count of unique vehicle trajectories, and C_h is the hourly count of vehicles to pass the count station. The hourly INDOT counts, hourly vehicle trajectory counts, and resulting hourly percent penetration for an I-70 count station in Indiana for August 2, 2021 are shown in Figure 7.3.

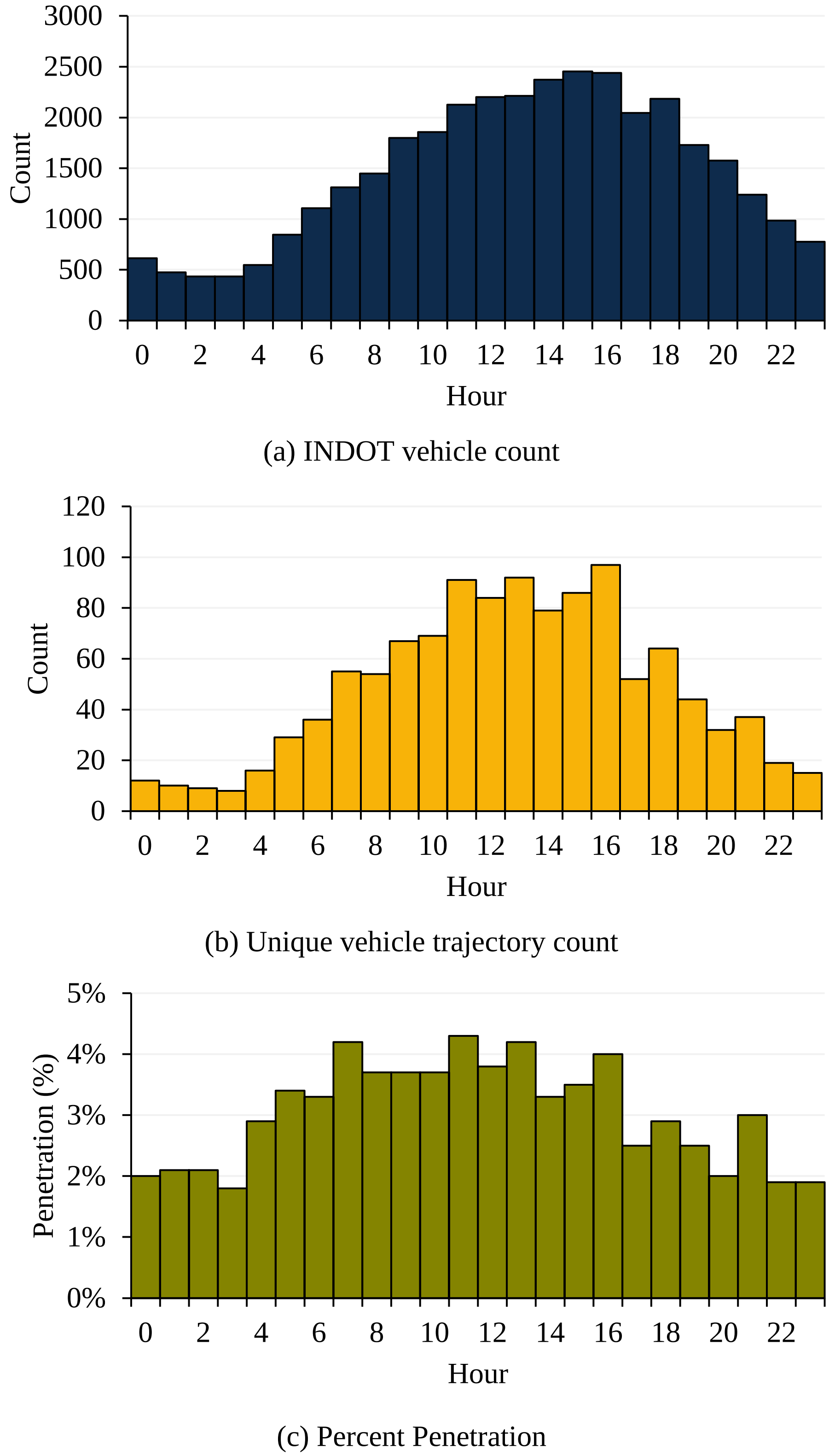


Figure 7.3. Hourly counts and percent penetration for Indiana station 950106 (I-70 MM 25.8) on Monday August 2, 2021

The daily percent penetration was determined by

$$D_p = \left(\frac{\sum V_h}{\sum C_h}\right)100 \qquad \text{Eq. 2}$$

Where D_p is the daily percent penetration, V_h is the hourly count of the vehicle trajectories, and C_h is the hourly count of the vehicles to across the count station. Table 7.2 contains the daily counts and resulting daily penetration for an I-70 location in Indiana.

The monthly percent penetration is calculated using the daily counts from the entire month using

$$M_p = \left(\frac{\sum V_d}{\sum C_d}\right)100 \qquad \text{Eq. 3}$$

where M_p is the monthly percent penetration, V_d is the daily count of vehicle trajectories, and C_d is the daily count of the vehicles to cross the count station. Table 7.3 contains the number of INDOT counts and vehicle trajectory counts the 31 days in August 2021. The resulting monthly penetration is shown at the bottom. This methodology was replicated to determine statewide, monthly percent penetration. The statewide, monthly percent penetration is calculated using the monthly counts from the stations using

$$S_p = \left(\frac{\sum V_m}{\sum C_m}\right)100 \qquad \text{Eq. 4}$$

where S_p is the statewide, monthly percent penetration, V_m is the monthly count of vehicle trajectories, and C_m is the monthly count of the vehicles to cross the count station.

A weighted average approach of aggregating raw counts, instead of percentages, was chosen to eliminate the effects of outlier hourly or daily percent penetrations. Additionally, hours and stations with missing or incomplete DOT data were removed from the percent penetration calculations.

The percent penetration hourly trend was the very similar across all 11 states, an example for Indiana is shown in Figure 7.6. Typically, the percent penetration is the highest and is relatively constant during the daylight hours. Since the dataset used in this study contains only passenger vehicles, as the number of passenger vehicles dropped during the evening and nighttime hours and the number of commercial vehicles decreased at a lesser rate, the percent penetration dropped to a low point between 1am and 3am before beginning to rebound as passenger vehicles reenter the road network.

Between August 2020 and August 2021, the overall percent penetration across all stations and states rose from 3.8% to 3.9%. Of the 11 states, 9 states saw an increase in percent penetration. The average increase was 0.14%. Minnesota and Texas were the two states that saw a decrease in percent penetration. Minnesota's decreased by 0.5% (attributable to a couple high percent penetration stations reporting in August 2020, but not August 2021), and Texas's decreased by 0.03%. Of the 315 stations reporting data in both August 2020 and August 2021, 85% saw an increase in percent penetration. The average percent increase was 0.7%. Figures detailing the differences between August 2020 and August 2021 are presented in section 6.4 Aggregate Results and section 6.5 Disaggregate Results.

Table 7.2. Hourly INDOT and vehicle trajectory counts and the resulting penetration for Indiana station 950106 (I-70 MM 25.8) on Monday August 2, 2021

Time (hrs)	**Count**		**% Penetration**
	INDOT	**Veh. Traj.**	
0:00	614	12	2.0
1:00	476	10	2.1
2:00	433	9	2.1
3:00	435	8	1.8
4:00	546	16	2.9
5:00	846	29	3.4
6:00	1105	36	3.3
7:00	1313	55	4.2
8:00	1448	54	3.7
9:00	1800	67	3.7
10:00	1857	69	3.7
11:00	2127	91	4.3
12:00	2203	84	3.8
13:00	2213	92	4.2
14:00	2373	79	3.3
15:00	2455	86	3.5
16:00	2438	97	4.0
17:00	2045	52	2.5
18:00	2185	64	2.9
19:00	1729	44	2.5
20:00	1576	32	2.0
21:00	1240	37	3.0
22:00	984	19	1.9
23:00	775	15	1.9
Total	**35216**	**1157**	**3.3**

Table 7.3. August 2021 summary for Indiana station 950106 (I-70 MM 25.8)

Date	Count		% Penetration
	INDOT	Veh. Traj.	
8/1/2021	36480	1602	4.4
8/2/2021	35216	1157	3.3
8/3/2021	36395	1086	3.0
8/4/2021	38584	1216	3.2
8/5/2021	39079	1175	3.0
8/6/2021	41127	1547	3.8
8/7/2021	35863	1333	3.7
8/8/2021	35359	1661	4.7
8/9/2021	35583	1272	3.6
8/10/2021	36766	1085	3.0
8/11/2021	37591	1126	3.0
8/12/2021	39543	1312	3.3
8/13/2021	41629	1569	3.8
8/14/2021	37935	1500	4.0
8/15/2021	37331	1664	4.5
8/17/2021	35737	967	2.7
8/18/2021	38100	1203	3.2
8/19/2021	39389	1266	3.2
8/20/2021	40504	1458	3.6
8/21/2021	34836	1382	4.0
8/22/2021	34905	1493	4.3
8/23/2021	33286	1148	3.4
8/24/2021	35061	1003	2.9
8/25/2021	36965	996	2.7
8/26/2021	38332	1192	3.1
8/27/2021	38611	1369	3.5
8/28/2021	33535	1259	3.8
8/29/2021	31780	1284	4.0
8/30/2021	32465	989	3.0
8/31/2021	35353	1030	2.9
Total	**1103340**	**38344**	**3.5**

7.4 Aggregate Results

7.4.1 Indiana

A longitudinal analysis for fifteen months between July 2019 and February 2022 was completed, shown in Figure 7.4. In July 2019, the month used in the SR-37 hard-braking and hard-acceleration crash analysis discussed in the earlier chapters, the percent penetration was under 2%. The percent penetration then doubled by January 2020. This increase is likely due to an increase in the amount of data provided to the third-party data collector rather than a massive increase in connected vehicles purchased. COVID-19 pandemic restrictions began in March 2020, which led to a decrease in passenger vehicles on the road. While volume and percent penetration are independent of each other, a slight decrease in penetration occurred after the start of the COVID-19 restrictions. The data used in this study is collected from passenger vehicles only. Since passenger vehicle traffic decreased at a faster rate and greater magnitude than truck traffic, the percent penetration dipped slightly (Goenaga et al., 2021). As the pandemic wore on, the percent penetration rose slightly and then hovered in the 4.5% - 5% range.

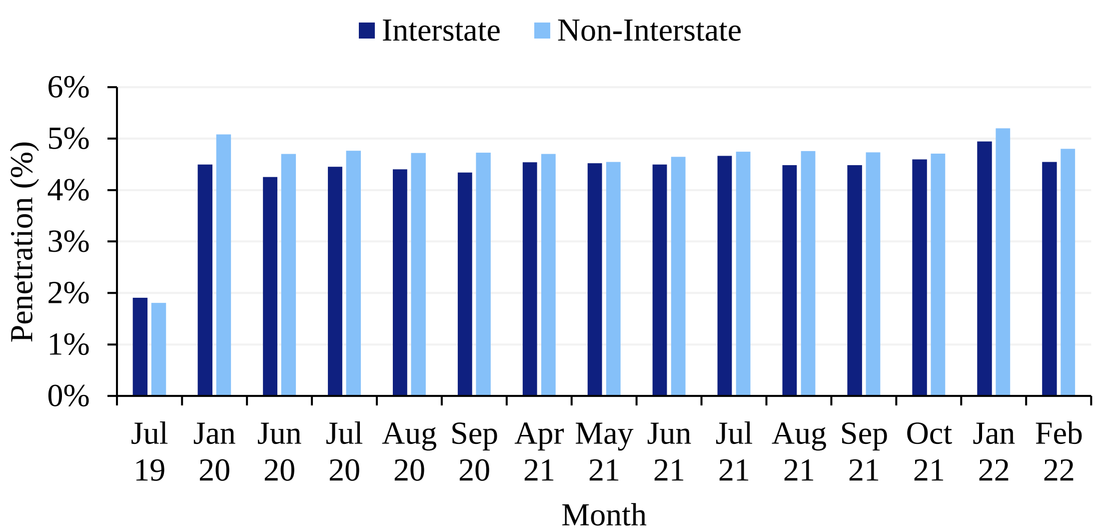


Figure 7.4. Average monthly penetration over time by road type for Indiana

In addition to a multi-year analysis, day of week and time-of-day analyses were performed. Figure 7.5 shows the average percent penetration by day of week aggregated over August 2021 for all count stations in Indiana. Percent penetration is at its lowest during the middle of the work week, Tuesday, Wednesday, and Thursday, and at its highest on Sundays. Interestingly, while the difference in percent penetration between non-interstates and interstates remains fairly constant between Tuesday and Thursday, the difference begins to shrink on Friday until it is negligible on Sunday. Perhaps, this could show the effect of commercial truckers taking time off for the weekend. Figure 7.6 shows the average percent penetration by time-of-day aggregated over August 2021 weekdays for all count stations in Indiana. Percent penetration is at its lowest during the early morning hours when the commercial truck volume is relatively high and passenger volume is relatively low. As passenger vehicles begin entering the roadways, the percent penetration jumps up to 4.5% - 5%, where it stays until about 7:00pm.

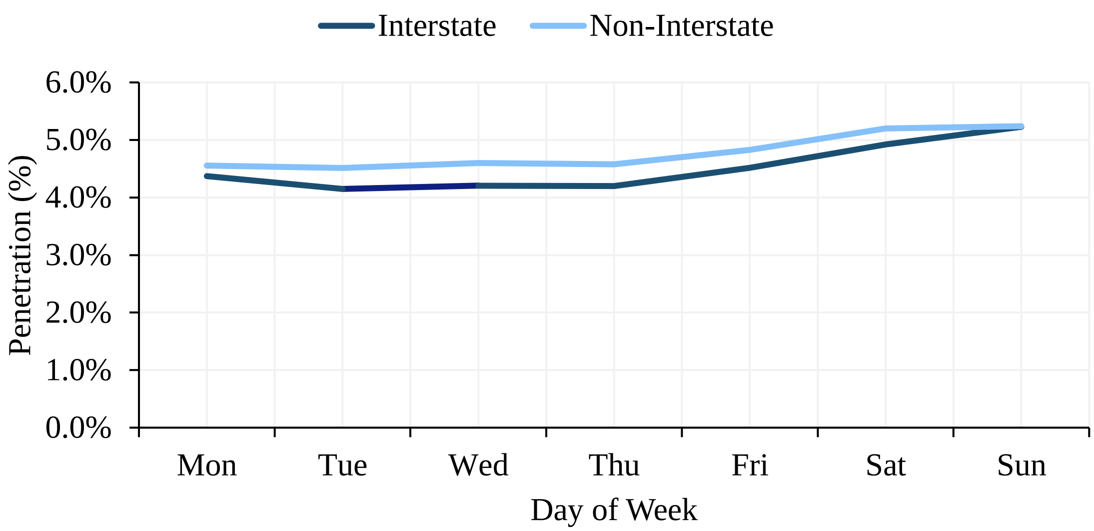


Figure 7.5. Average percent penetration by day of week for August 2021 aggregated over all stations in Indiana

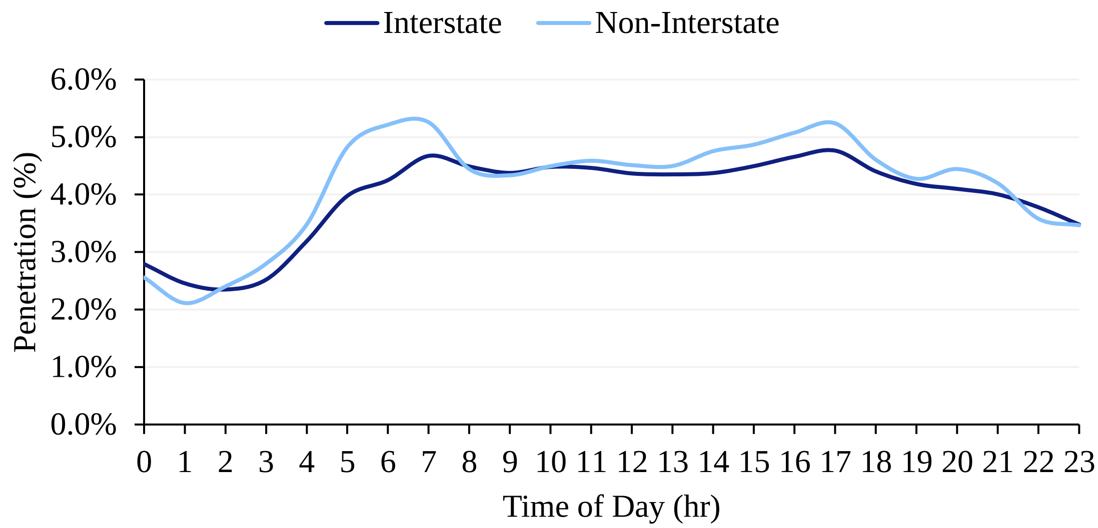
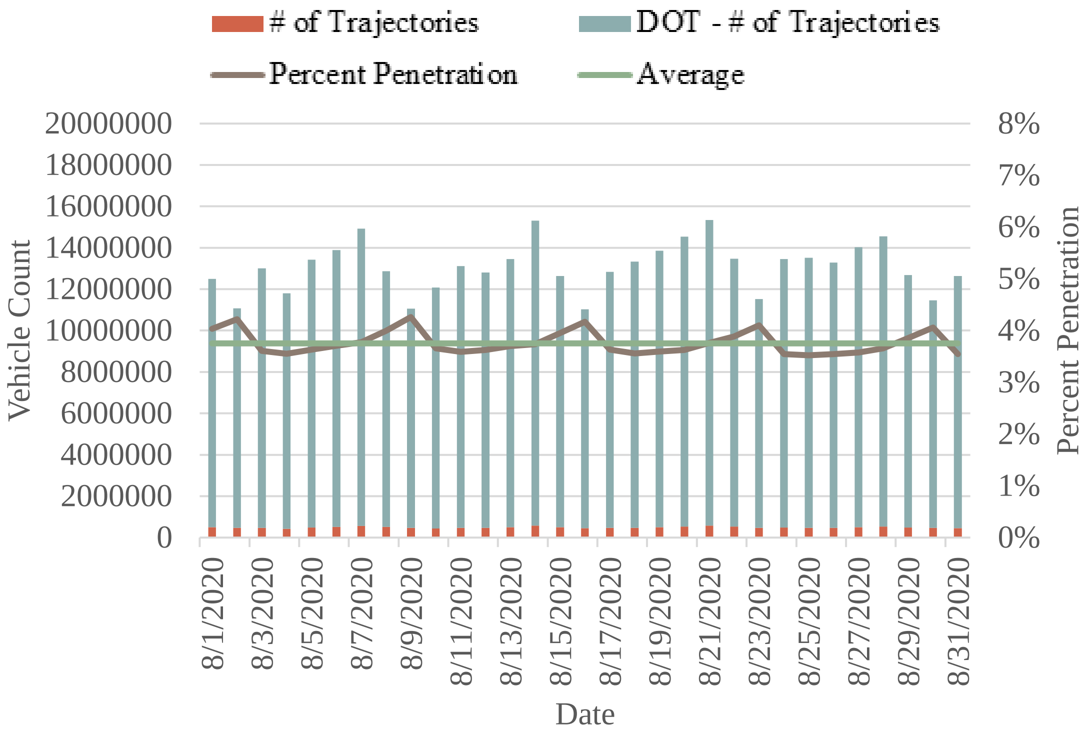


Figure 7.6. Aggregated average percent penetration by time-of-day for August 2021 aggregated over all stations in Indiana

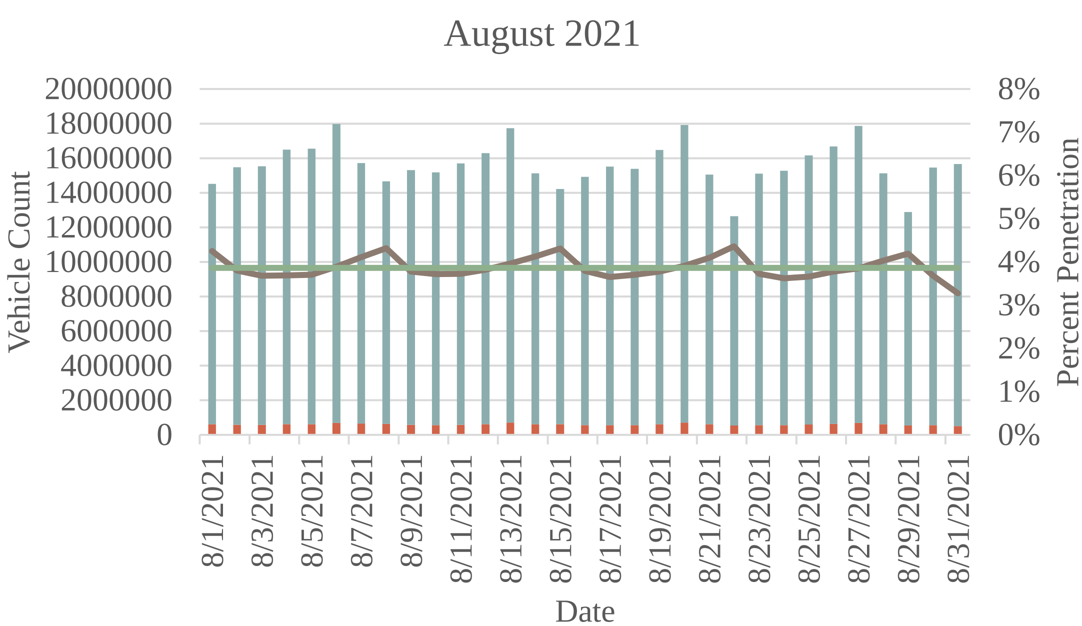
7.4.2 Additional States

Once Indiana's percent penetration had been analyzed, the study was broadened to include 10 other states with a focus on the months of August 2020 and August 2021. In total, roughly 15 million connected vehicle trajectory journeys in August 2020 and 19 million trajectory journeys in August 2021 were compared to 405 million DOT collected vehicle counts in August 2020 and 485 million vehicle counts in August 2021. The overall average percent penetration was 3.8% in August 2020 and 3.9% in August 2021. Figure 7.7 depicts the number of connected vehicle trajectory journeys and number of DOT collected vehicle counts minus the number of connected vehicle trajectory journeys. Additionally, Figure 7.7 shows the average percent penetration by day and for the whole month. The sawtooth pattern exhibited by the percent penetration can be explained by the trend shown in Figure 7.5. The percent penetration is at its lowest during the work week, but then sees an increase during the weekend.

Figure 7.8 drills down to the percent penetration for each of the 11 states for August 2020 and August 2021. For the majority of the states, percent penetration increased at least slightly between August 2020 and August 2021. The differences in the amount of change between August 2020 and August 2021 between the 11 states can possibly be attributed to the variation in number and types of stations reporting data over the two months (Table 7.1).



(a) August 2020



(b) August 2021

Figure 7.7. Summary plots of all stations depicting number of connect vehicle trajectory journeys, number of DOT collected vehicle counts minus the number of connected vehicle trajectory journeys, and the average percent penetration by day and for the month

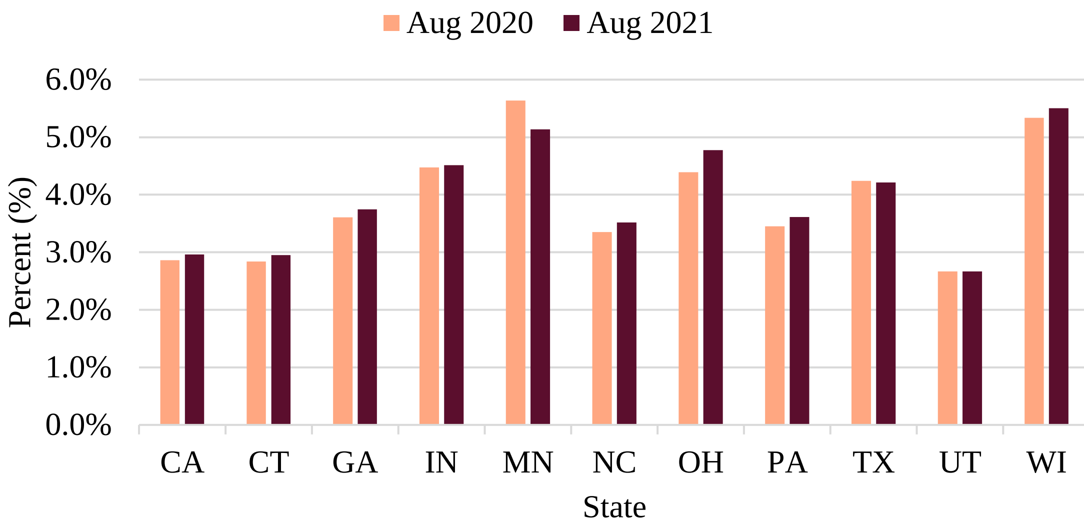
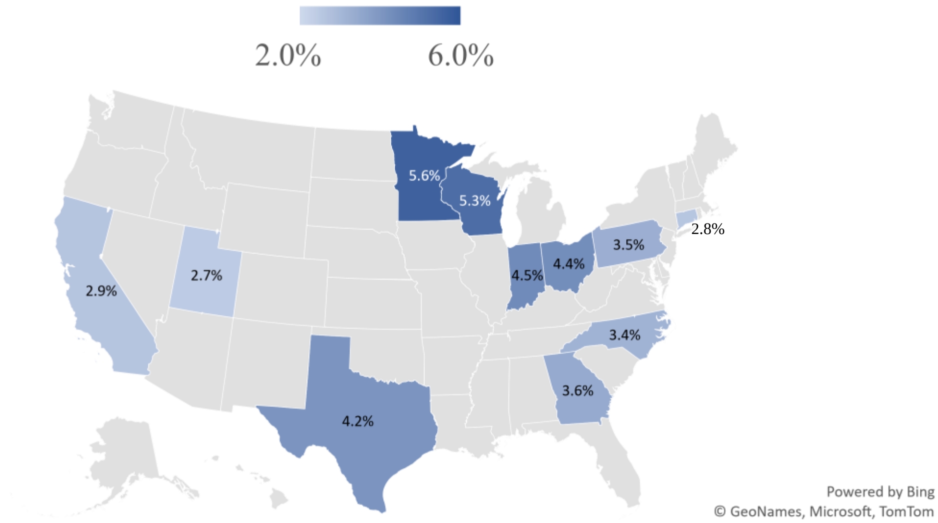
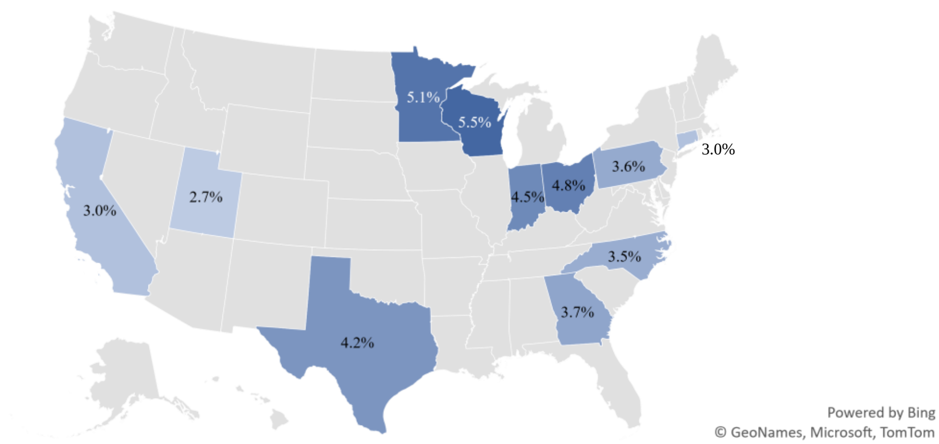


Figure 7.8. Percent penetration for 11 states for August 2020 and August 2021

Figure 7.9 presents similar information to Figure 7.8; however, the percent penetration is shown geographically. Penetration tends to be higher in the Midwest than in the more southern, coastal states. While the exact reasoning behind the differences in percent penetration is beyond the scope of this project, this thesis does offer some speculation. The data set used in this study doesn't include all vehicle makes. Perhaps, some states have a higher percentage of the vehicle makes included in the data than other states. Additionally, due to the lack of winter weather and subsequent salt and brine distribution, vehicles may be able to last longer in southern states leading to a larger number of older non-connected vehicles on the roadways.



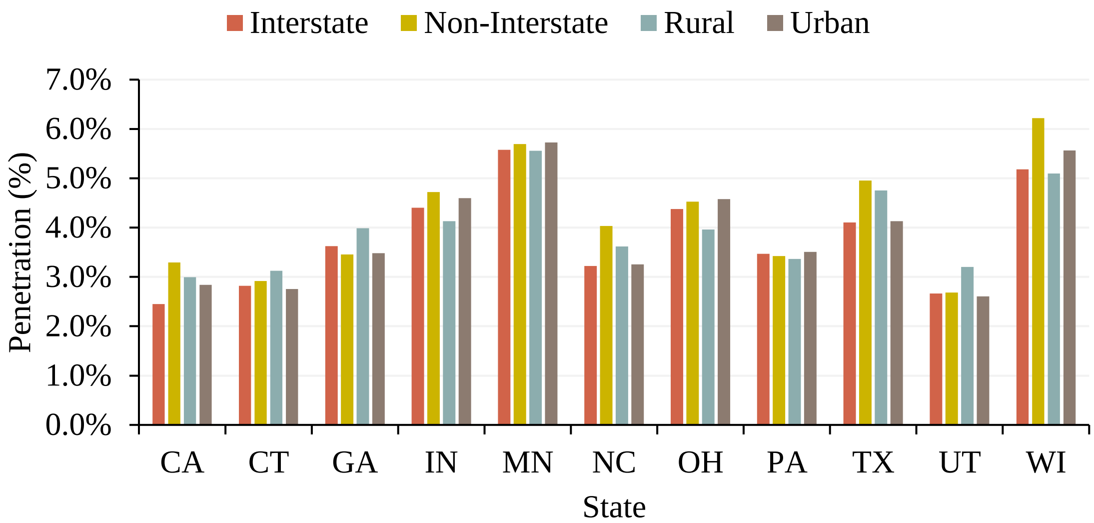
(a) August 2020



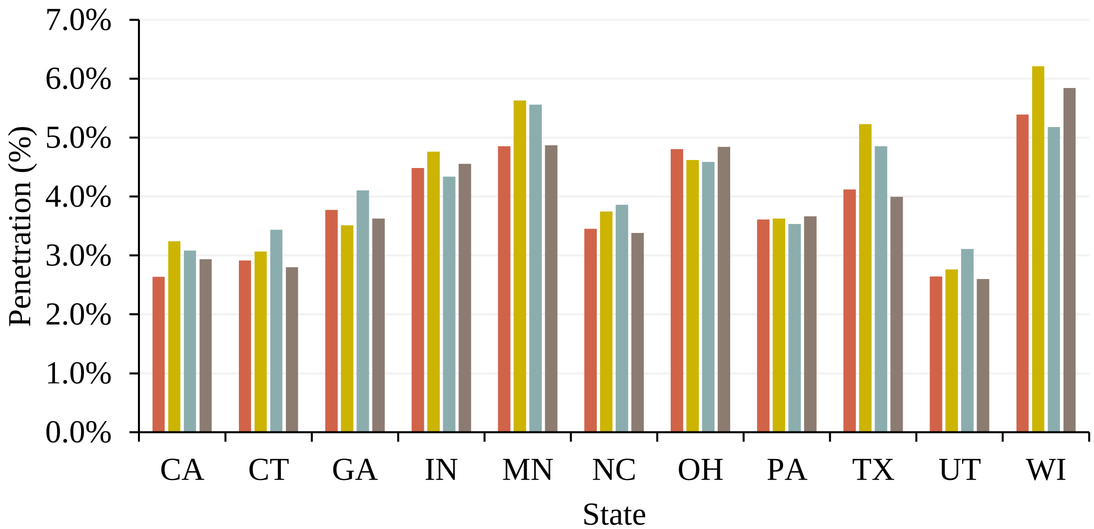
(b) August 2021

Figure 7.9. Spatial distribution of percent penetration for 11 states

Figure 7.10 drills down even further and provides the percent penetration for August 2020 and August 2021 for all 11 states broken down by interstate, non-interstate, rural, and urban stations. Note each station was represented twice as each station is any combination of interstate / non-interstate and rural / urban. On average, the percent penetration varied by 0.6% between the 4 categories with the greatest difference being 1.1% for August 2020 and 1.2% for August 2021 and the smallest difference being 0.1% for both August 2020 and August 2021.



(a) August 2020



(b) August 2021

Figure 7.10. Average percent penetration by state for interstate, non-interstates, rural, and urban stations

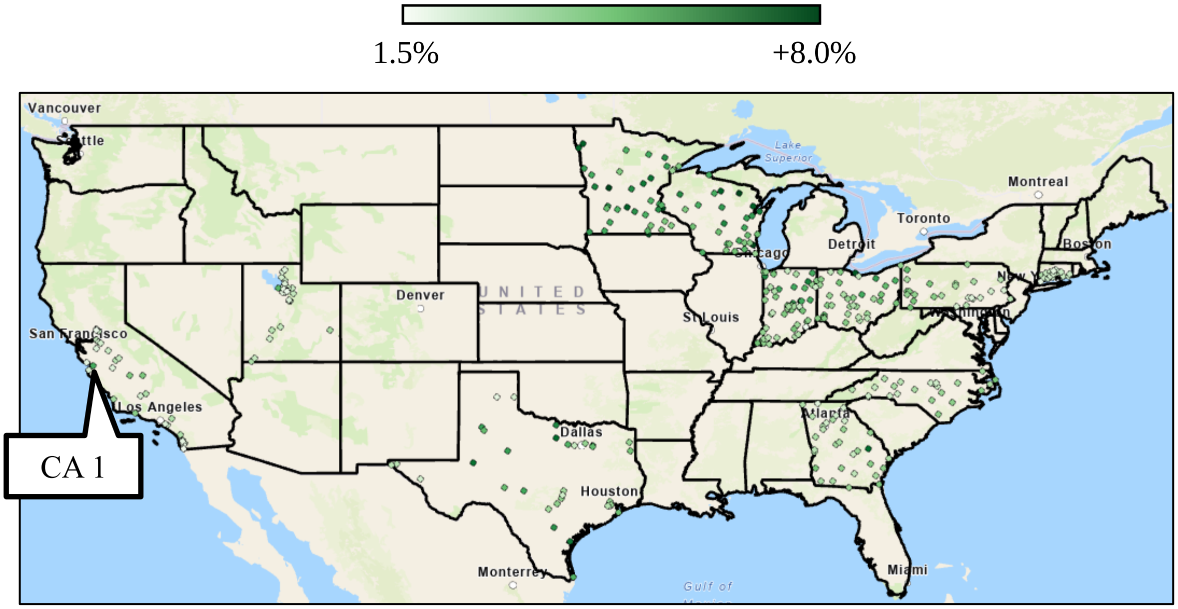
Finally, Table 7.4 presents a station summary table showing the lowest, median, and highest percent penetrations for each state in August 2021. For interstate stations, the lowest percent penetration was a California station with a percent penetration of 2.1%. Meanwhile, for non-interstate stations, an Indiana station had the lowest percent penetration at 1.6%. For both interstate and non-interstate categories, Wisconsin had the stations with the highest percent penetration, 18% for an interstate station and 10% for a non-interstate station. The median values across all 11 states were 4.1% and 4.3% for interstate and non-interstates, respectively. The interquartile range for both types combined was between 3.3% and 5.0% with a mean of 4.2%. As a reminder, Table 7.1 provides the sample size for the number of interstate and non-interstate stations. The number of interstates count stations evaluated ranged from 9 to 34 for CA / CT and IN, respectively. The number of non-interstates count stations evaluated ranged from 6 to 29 for CT and IN, respectively.

Table 7.4. Station summary table for interstate and non-interstate percent penetrations for 11 states in August 2021

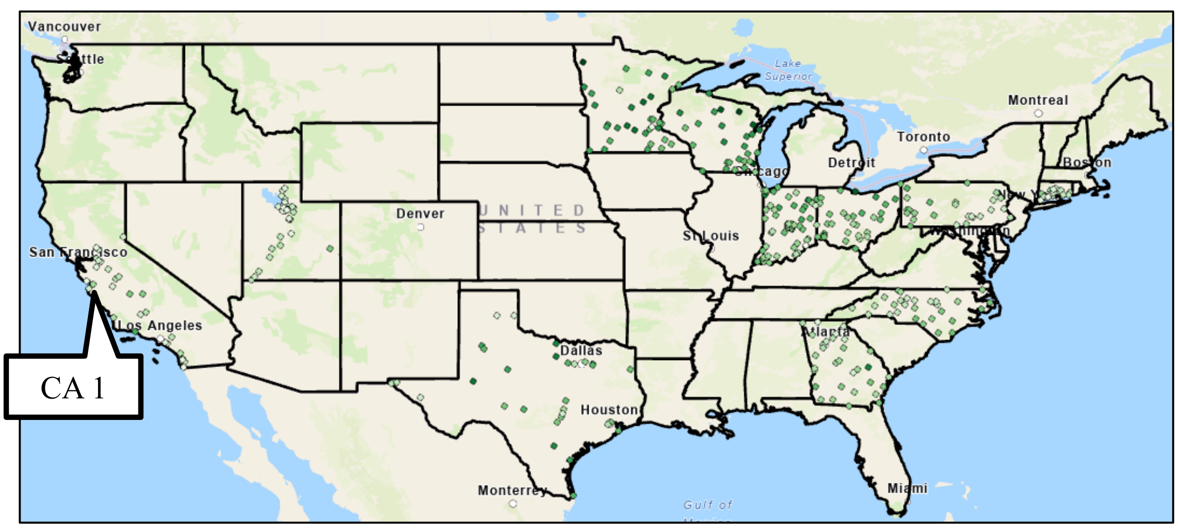
	Minimum		**Median**		**Maximum**	
	Interstate	**Non-Interstate**	**Interstate**	**Non-Interstate**	**Interstate**	**Non-Interstate**
CA	2.1%	2.3%	2.7%	3.3%	2.9%	5.5%
CT	2.3%	2.5%	3.0%	3.2%	4.3%	3.4%
GA	3.1%	2.4%	3.9%	3.7%	4.6%	6.7%
IN	3.4%	1.6%	4.4%	4.6%	6.2%	6.7%
MN	2.1%	3.5%	5.0%	5.9%	6.1%	9.0%
NC	3.1%	3.0%	3.5%	4.2%	4.8%	4.8%
OH	3.8%	3.6%	4.8%	4.1%	6.0%	7.5%
PA	2.9%	2.8%	3.7%	3.8%	5.2%	5.0%
TX	2.6%	3.2%	4.5%	5.5%	6.4%	7.0%
UT	2.3%	2.2%	2.7%	2.7%	3.5%	4.5%
WI	4.3%	4.5%	5.2%	6.0%	18.0%	10.0%
All	2.1%	1.6%	4.1%	4.3%	18.0%	10.0%

7.5 Disaggregate Results

Once the aggregate results were analyzed for each of the 11 states, the individual stations were analyzed. Figure 7.11 shows the percent penetration by station for August 2020 and August 2021. The percent penetration at individual stations ranged from 1.6% to 16.3% in August 2020 and 1.6% to 18.0% in August 2021. Figure 7.12, Figure 7.13, and Figure 7.14 present box plots of the percent penetration by station by hour, by station by day, and by station. 99% of the August 2020 and August 2021 hours analyzed had percent penetrations of 11% or less (472,000 out of 479,000 hours). 98% of the August 2020 and August 2021 days analyzed had percent penetrations between 2% and 8% (19,800 out of 20,100 days). The following sections will examine some outliers from California, Minnesota, Texas, and Wisconsin. Appendix B contains additional examples of specific stations for all 11 states.



(a) August 2020



(b) August 2021

Figure 7.11. Monthly percent penetration by station

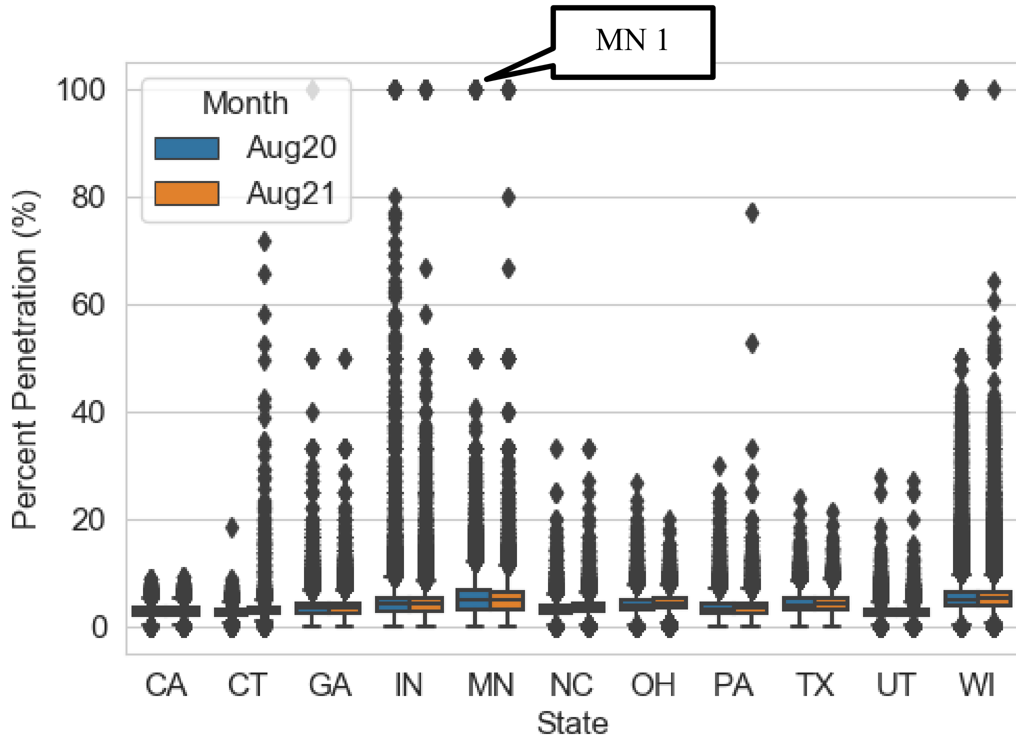


Figure 7.12. Box plot: Percent penetration by station by hour

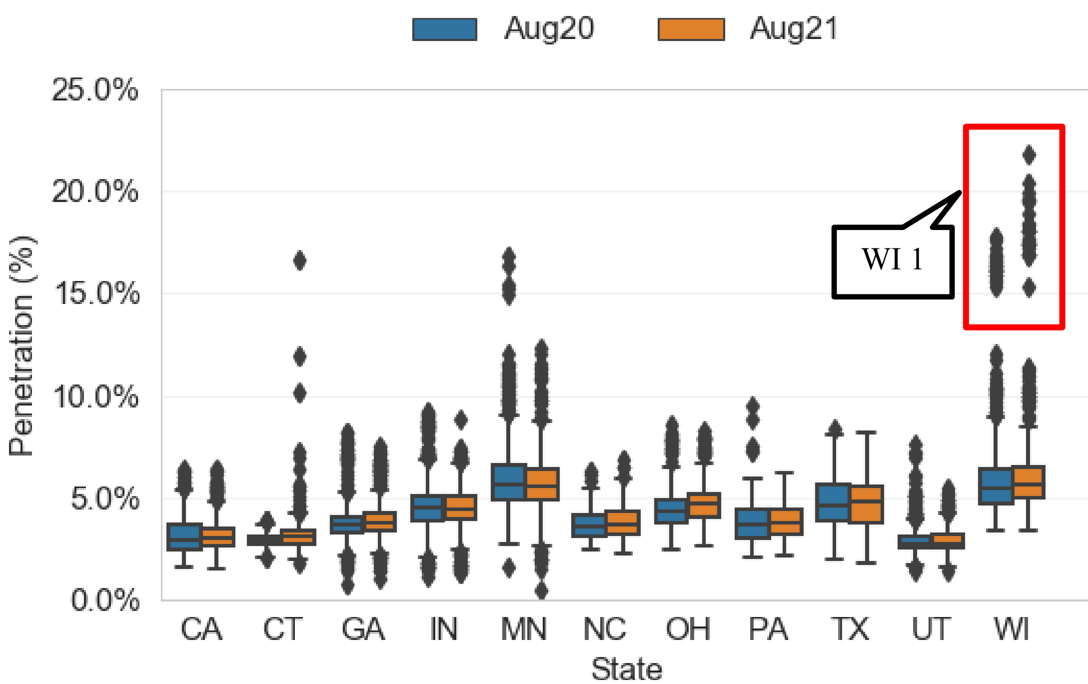


Figure 7.13. Box plot: Percent penetration by station by day

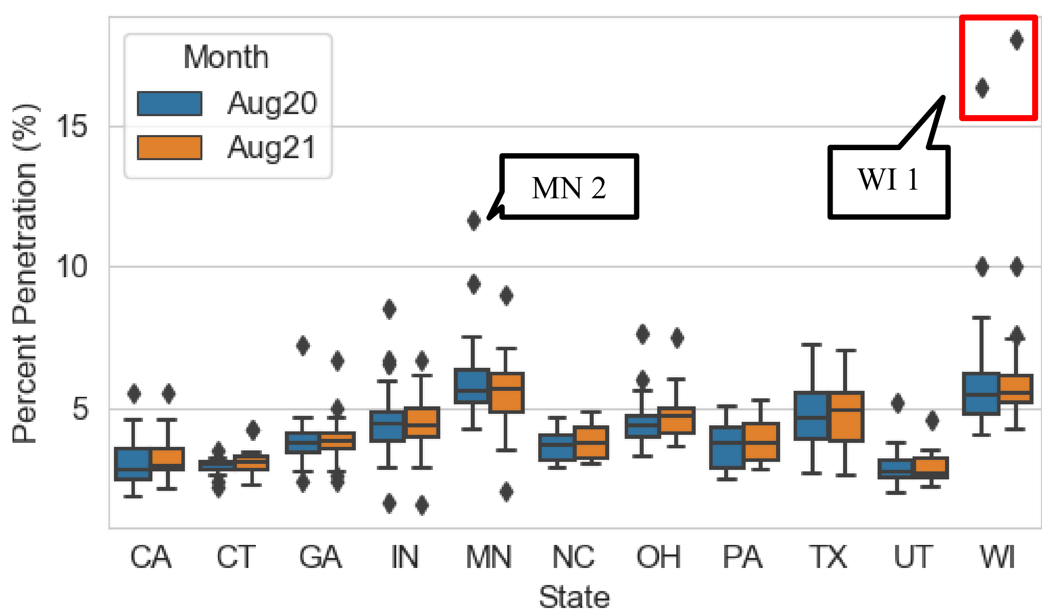


Figure 7.14. Box plot: Percent penetration by station

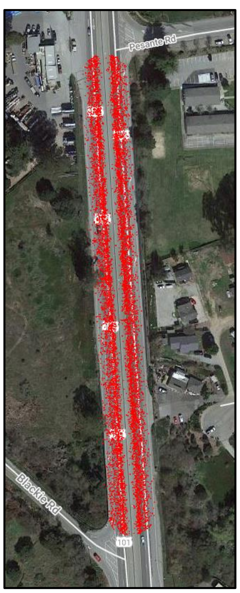
7.5.1 CA: CA-25

CA-25 is identified as CA 1 in Figure 7.11 and Figure 7.15. Unlike the majority of the other states analyzed in this study, Caltrans treats each direction, ramp, and high occupancy lane as a unique station. Therefore, in order to determine the full roadway volume, the appropriate Caltrans stations were summed together and treated as one station id. Additionally, not every hour was 100% observed. Hours with less than a 100% observation rate were excluded along with the corresponding connected vehicle trajectory counts for that same hour. CA-25 consists of two Caltrans stations: 501019111 and 501019112.

CA-25 was chosen for further analysis as the percent penetration was 5.5% in August 2020, but 3.9% in August 2021. Figure 7.15 shows the location of CA-25. Figure 7.16 depicts the percent penetration calculations for Monday August 3, 2020 and Tuesday August 3, 2021. Adjacent to the calculations are maps with the connected vehicle trajectory points plotted. Table 7.5 displays the hourly percent penetration for both August 3rds. The reason for this large decrease in percent penetration can be explained by the DOT traffic counts seeing a 46% increase while the connected vehicle journey counts only saw a 6% increase. The underlying cause for this discrepancy in percent increase is currently unknown, but it does highlight the value of aggregating over numerous sites so that such anomalies can be accounted for without overly skewing the data.

Figure 7.17 shows screen captures of PeMS for Caltrans stations 501019111 and 501019112 for hourly counts on August 3, 2020 and August 3, 2021 (Caltrans, n.d.).

Figure 7.15. Location of California station CA-25



Date: Mon Aug 3, 2020

Trajectory points: 9134

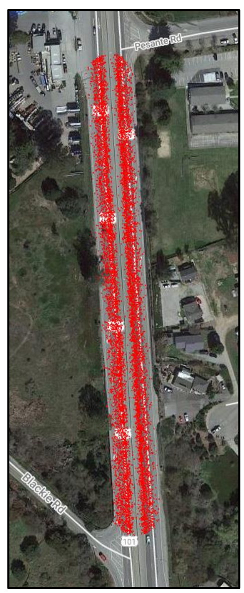
DOT: 44635

Journeys: 2454

Percent Penetration:

2454 / 44635 = 5.5%

(a) August 3, 2020



Date: Tue Aug 3, 2021

Trajectory points: 10240

DOT: 71882

Journeys: 2744

Percent Penetration:

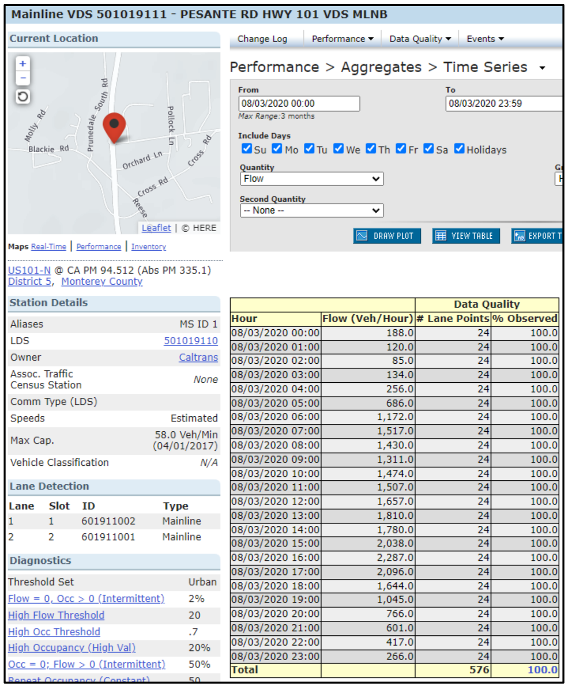
2744 / 71882= 3.8%

(b) August 3, 2021

Figure 7.16. Connected vehicle trajectory points and the associated percent penetration calculations for California station CA-25

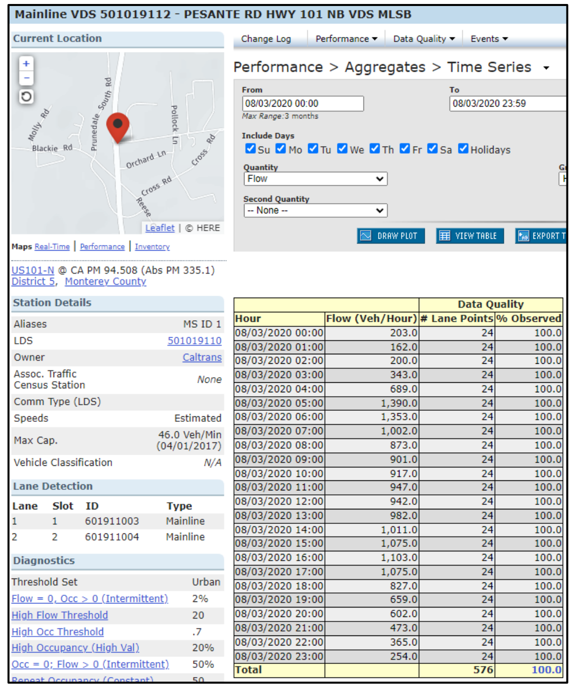
Table 7.5. Percent penetration calculations for August 3, 2020 and August 3, 2021 for California station CA-25

2020					2021				
Date	**Hour**	**DOT Count**	**CV Count**	**Percent**	**Date**	**Hour**	**DOT Count**	**CV Count**	**Percent**
8/3/2020	0	391	18	4.6%	8/3/2021	0	525	6	1.1%
8/3/2020	1	282	14	5.0%	8/3/2021	1	439	13	3.0%
8/3/2020	2	285	9	3.2%	8/3/2021	2	464	8	1.7%
8/3/2020	3	477	21	4.4%	8/3/2021	3	741	20	2.7%
8/3/2020	4	945	50	5.3%	8/3/2021	4	1419	51	3.6%
8/3/2020	5	2076	87	4.2%	8/3/2021	5	3334	102	3.1%
8/3/2020	6	2525	149	5.9%	8/3/2021	6	4130	158	3.8%
8/3/2020	7	2519	119	4.7%	8/3/2021	7	4169	189	4.5%
8/3/2020	8	2303	134	5.8%	8/3/2021	8	3572	146	4.1%
8/3/2020	9	2212	143	6.5%	8/3/2021	9	3209	132	4.1%
8/3/2020	10	2391	128	5.4%	8/3/2021	10	3638	162	4.5%
8/3/2020	11	2454	148	6.0%	8/3/2021	11	3879	167	4.3%
8/3/2020	12	2599	163	6.3%	8/3/2021	12	4084	164	4.0%
8/3/2020	13	2792	155	5.6%	8/3/2021	13	4135	147	3.6%
8/3/2020	14	2791	165	5.9%	8/3/2021	14	4432	168	3.8%
8/3/2020	15	3113	179	5.8%	8/3/2021	15	5059	201	4.0%
8/3/2020	16	3390	179	5.3%	8/3/2021	16	5289	209	4.0%
8/3/2020	17	3171	203	6.4%	8/3/2021	17	5564	202	3.6%
8/3/2020	18	2471	138	5.6%	8/3/2021	18	4253	154	3.6%
8/3/2020	19	1704	78	4.6%	8/3/2021	19	3219	125	3.9%
8/3/2020	20	1368	67	4.9%	8/3/2021	20	2431	83	3.4%
8/3/2020	21	1074	50	4.7%	8/3/2021	21	1834	71	3.9%
8/3/2020	22	782	33	4.2%	8/3/2021	22	1306	37	2.8%
8/3/2020	23	520	24	4.6%	8/3/2021	23	757	29	3.8%
8/3/2020	**Total**	**44635**	**2454**	**5.5%**	**8/3/2021**	**Total**	**71882**	**2744**	**3.8%**



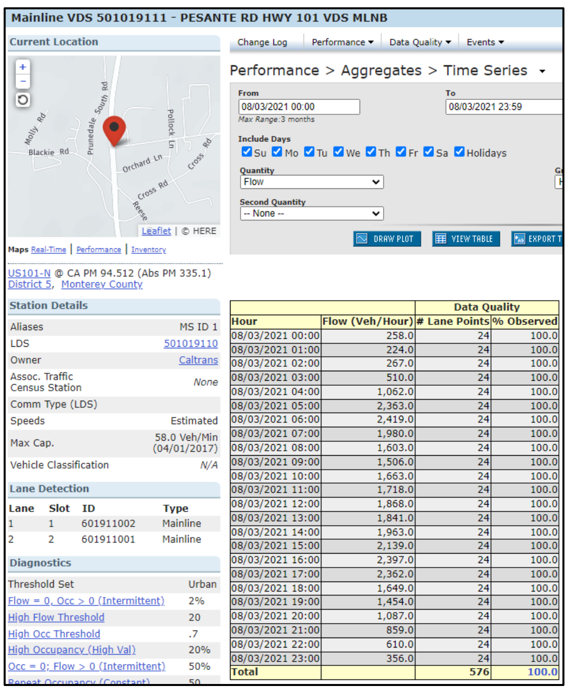
Hour	Flow (Veh/Hour)	Data Quality: # Lane Points	Data Quality: % Observed
08/03/2020 00:00	188.0	24	100.0
08/03/2020 01:00	120.0	24	100.0
08/03/2020 02:00	85.0	24	100.0
08/03/2020 03:00	134.0	24	100.0
08/03/2020 04:00	256.0	24	100.0
08/03/2020 05:00	686.0	24	100.0
08/03/2020 06:00	1,172.0	24	100.0
08/03/2020 07:00	1,517.0	24	100.0
08/03/2020 08:00	1,430.0	24	100.0
08/03/2020 09:00	1,311.0	24	100.0
08/03/2020 10:00	1,474.0	24	100.0
08/03/2020 11:00	1,507.0	24	100.0
08/03/2020 12:00	1,657.0	24	100.0
08/03/2020 13:00	1,810.0	24	100.0
08/03/2020 14:00	1,780.0	24	100.0
08/03/2020 15:00	2,038.0	24	100.0
08/03/2020 16:00	2,287.0	24	100.0
08/03/2020 17:00	2,096.0	24	100.0
08/03/2020 18:00	1,644.0	24	100.0
08/03/2020 19:00	1,045.0	24	100.0
08/03/2020 20:00	766.0	24	100.0
08/03/2020 21:00	601.0	24	100.0
08/03/2020 22:00	417.0	24	100.0
08/03/2020 23:00	266.0	24	100.0
Total		576	100.0

(a) Station 501019111 - August 3, 2020



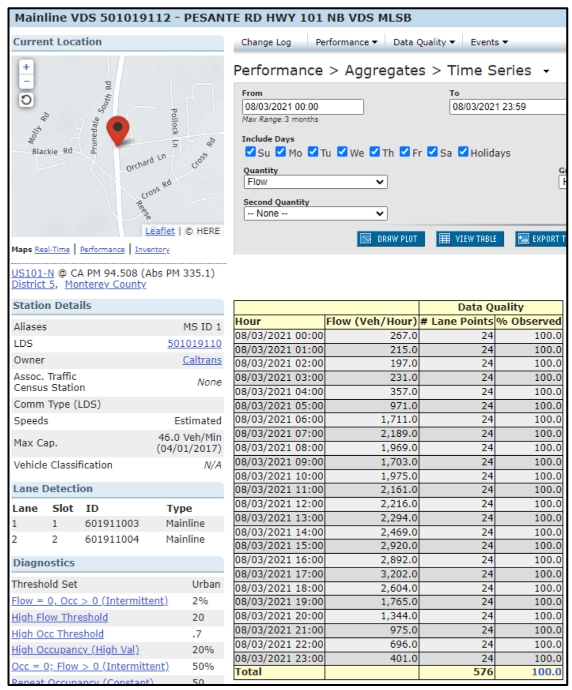
Hour	Flow (Veh/Hour)	Data Quality: # Lane Points	Data Quality: % Observed
08/03/2020 00:00	203.0	24	100.0
08/03/2020 01:00	162.0	24	100.0
08/03/2020 02:00	200.0	24	100.0
08/03/2020 03:00	343.0	24	100.0
08/03/2020 04:00	689.0	24	100.0
08/03/2020 05:00	1,390.0	24	100.0
08/03/2020 06:00	1,353.0	24	100.0
08/03/2020 07:00	1,002.0	24	100.0
08/03/2020 08:00	873.0	24	100.0
08/03/2020 09:00	901.0	24	100.0
08/03/2020 10:00	917.0	24	100.0
08/03/2020 11:00	947.0	24	100.0
08/03/2020 12:00	942.0	24	100.0
08/03/2020 13:00	982.0	24	100.0
08/03/2020 14:00	1,011.0	24	100.0
08/03/2020 15:00	1,075.0	24	100.0
08/03/2020 16:00	1,103.0	24	100.0
08/03/2020 17:00	1,075.0	24	100.0
08/03/2020 18:00	827.0	24	100.0
08/03/2020 19:00	659.0	24	100.0
08/03/2020 20:00	602.0	24	100.0
08/03/2020 21:00	473.0	24	100.0
08/03/2020 22:00	365.0	24	100.0
08/03/2020 23:00	254.0	24	100.0
Total		576	100.0

(b) Station 501019112 – August 3, 2020



Hour	Flow (Veh/Hour)	Data Quality: # Lane Points	Data Quality: % Observed
08/03/2021 00:00	258.0	24	100.0
08/03/2021 01:00	224.0	24	100.0
08/03/2021 02:00	267.0	24	100.0
08/03/2021 03:00	510.0	24	100.0
08/03/2021 04:00	1,062.0	24	100.0
08/03/2021 05:00	2,363.0	24	100.0
08/03/2021 06:00	2,419.0	24	100.0
08/03/2021 07:00	1,980.0	24	100.0
08/03/2021 08:00	1,603.0	24	100.0
08/03/2021 09:00	1,506.0	24	100.0
08/03/2021 10:00	1,663.0	24	100.0
08/03/2021 11:00	1,718.0	24	100.0
08/03/2021 12:00	1,868.0	24	100.0
08/03/2021 13:00	1,841.0	24	100.0
08/03/2021 14:00	1,963.0	24	100.0
08/03/2021 15:00	2,139.0	24	100.0
08/03/2021 16:00	2,397.0	24	100.0
08/03/2021 17:00	2,362.0	24	100.0
08/03/2021 18:00	1,649.0	24	100.0
08/03/2021 19:00	1,454.0	24	100.0
08/03/2021 20:00	1,087.0	24	100.0
08/03/2021 21:00	859.0	24	100.0
08/03/2021 22:00	610.0	24	100.0
08/03/2021 23:00	356.0	24	100.0
Total		576	100.0

(c) Station 501019111 – August 3, 2021



Hour	Flow (Veh/Hour)	Data Quality: # Lane Points	Data Quality: % Observed
08/03/2021 00:00	267.0	24	100.0
08/03/2021 01:00	215.0	24	100.0
08/03/2021 02:00	197.0	24	100.0
08/03/2021 03:00	231.0	24	100.0
08/03/2021 04:00	357.0	24	100.0
08/03/2021 05:00	971.0	24	100.0
08/03/2021 06:00	1,711.0	24	100.0
08/03/2021 07:00	2,189.0	24	100.0
08/03/2021 08:00	1,969.0	24	100.0
08/03/2021 09:00	1,703.0	24	100.0
08/03/2021 10:00	1,975.0	24	100.0
08/03/2021 11:00	2,161.0	24	100.0
08/03/2021 12:00	2,216.0	24	100.0
08/03/2021 13:00	2,294.0	24	100.0
08/03/2021 14:00	2,469.0	24	100.0
08/03/2021 15:00	2,920.0	24	100.0
08/03/2021 16:00	2,892.0	24	100.0
08/03/2021 17:00	3,202.0	24	100.0
08/03/2021 18:00	2,604.0	24	100.0
08/03/2021 19:00	1,765.0	24	100.0
08/03/2021 20:00	1,344.0	24	100.0
08/03/2021 21:00	975.0	24	100.0
08/03/2021 22:00	696.0	24	100.0
08/03/2021 23:00	401.0	24	100.0
Total		576	100.0

(d) Station 501019112 – August 3, 2021

Figure 7.17. Screen shots of California's CA-25 station traffic counts from Caltrans's PeMS (Caltrans, n.d.)

7.5.2 MN: 48

The next station to be analyzed is station 48 in Minnesota, identified as MN 1 in Figure 7.12. This station was chosen as an example site to explain the large variation in hourly percent penetrations show in Figure 7.12. Figure 7.18 shows the location of MN 1, and Figure 7.19 depicts the percent penetration calculations for 2am on August 21, 2021 along with a map of the associated trajectory points. As shown, the 100% percent penetration can be attributed to only one vehicle, a vehicle that reports to the connected vehicle dataset used in this study, passing the count station. Table 7.6 presents the hourly percent penetration for the entire day of August 21, 2021. While the daily percent penetration of station 48 on August 21, 2021 is 6.3%, percent penetration fluctuates between 0% and 100% over the course of the day. This station highlights the importance of aggregating over many hours, instead of relying on just one hour for calculating the percent penetration, especially for low volume stations.

The Minnesota traffic count information was downloaded for MnDOT's Data Product webpage (MnDOT, n.d.). Table 7.7 shows the hourly data collected from MnDOT for station 48 for August 21, 2021. The counts received were differentiated by direction; therefore, the directional counts were summed to represent the traffic counts for the entire roadway.

Figure 7.18. Location of Minnesota station 48

Date: Aug 21, 2021

Time: 2am

Trajectory points: 5

DOT: 1

Journeys: 1

Percent Penetration:

1 / 1 = 100%

Figure 7.19. Connected vehicle trajectory points and the associated percent penetration calculations for Minnesota station 48

Table 7.6. Percent penetration calculations for August 21, 2021 for Minnesota station 48

Date	Hour	DOT Count	CV Count	Percent
8/21/2021	0	1	0	0%
8/21/2021	1	4	1	25%
8/21/2021	2	1	1	100%
8/21/2021	3	0	0	0%
8/21/2021	4	3	0	0%
8/21/2021	5	3	0	0%
8/21/2021	6	5	0	0%
8/21/2021	7	20	0	0%
8/21/2021	8	20	3	15%
8/21/2021	9	32	3	9%
8/21/2021	10	42	1	2%
8/21/2021	11	35	3	9%
8/21/2021	12	28	0	0%
8/21/2021	13	41	1	2%
8/21/2021	14	33	2	6%
8/21/2021	15	35	1	3%
8/21/2021	16	33	2	6%
8/21/2021	17	23	1	4%
8/21/2021	18	28	3	11%
8/21/2021	19	26	2	8%
8/21/2021	20	23	1	4%
8/21/2021	21	10	2	20%
8/21/2021	22	18	1	6%
8/21/2021	23	11	2	18%
8/21/2021	**Total**	**475**	**30**	**6.3%**

Table 7.7. Hourly counts obtained from MnDOT for August 21, 2021 for Minnesota station 48

StationID	**48**	**48**	**Hour Total**
Direction	**NB**	**SB**	
Hour	**8/21/2021**	**8/21/2021**	
0	1	0	1
1	3	1	4
2	0	1	1
3	0	0	0
4	1	2	3
5	2	1	3
6	1	4	5
7	13	7	20
8	12	8	20
9	15	17	32
10	15	27	42
11	20	15	35
12	10	18	28
13	14	27	41
14	14	19	33
15	18	17	35
16	16	17	33
17	14	9	23
18	15	13	28
19	12	14	26
20	12	11	23
21	6	4	10
22	14	4	18
23	5	6	11
Total	**233**	**242**	**475**
Total	**475**		

7.5.3 MN: 1335

For the by station box plot (Figure 7.14), Minnesota station 1335, MN 2, was analyzed. This station is an example of an outlier station with a large percent penetration. Figure 7.20 shows the location of station 1335, and Figure 7.21 depicts the percent penetration calculations for August 9, 2020. Table 7.8 shows the hourly percent penetration for station 1335 on August 9, 2020.

Throughout the day of August 9, 2020, the percent penetration ranges from 2% at 2am to 41% at 9am. This station's August 2020 percent penetration of 11.6% is just over double the August 2020 percent penetration for the state of Minnesota. This points to the importance of monitoring many locations and not assuming that the statewide percent penetration is applicable to all locations.

Table 7.9 shows the hourly data collected from MnDOT for station 48 for August 21, 2021.

Figure 7.20. Location of Minnesota station 1335

Date: Aug 9, 2020

Trajectory points: 6591

DOT: 9256

Journeys: 1558

Percent Penetration:

1558 / 9256 = 17%

Figure 7.21. Connected vehicle trajectory points and the associated percent penetration calculations for Minnesota station 1335

Table 7.8. Percent penetration calculations for August 9, 2020 for Minnesota station 1335

Date	Hour	DOT Count	CV Count	Percent
8/9/2020	0	97	5	5%
8/9/2020	1	78	3	4%
8/9/2020	2	49	1	2%
8/9/2020	3	54	2	4%
8/9/2020	4	35	3	9%
8/9/2020	5	56	6	11%
8/9/2020	6	58	15	26%
8/9/2020	7	113	14	12%
8/9/2020	8	161	35	22%
8/9/2020	9	226	92	41%
8/9/2020	10	391	109	28%
8/9/2020	11	563	140	25%
8/9/2020	12	688	154	22%
8/9/2020	13	702	175	25%
8/9/2020	14	844	171	20%
8/9/2020	15	920	157	17%
8/9/2020	16	907	146	16%
8/9/2020	17	822	123	15%
8/9/2020	18	698	72	10%
8/9/2020	19	575	46	8%
8/9/2020	20	486	46	10%
8/9/2020	21	346	22	6%
8/9/2020	22	250	10	4%
8/9/2020	23	137	11	8%
8/9/2020	**Total**	**9256**	**1558**	**16.8%**

Table 7.9. Hourly counts obtained from MnDOT for August 9, 2020 for Minnesota station 1335

StationID	1335	1335	Hour Total
Direction	**EB**	**WB**	
Hour	**8/9/2020**	**8/9/2020**	
0	12	85	97
1	11	67	78
2	7	42	49
3	8	46	54
4	5	30	35
5	5	51	56
6	4	54	58
7	15	98	113
8	21	140	161
9	40	186	226
10	80	311	391
11	139	424	563
12	172	516	688
13	179	523	702
14	260	584	844
15	308	612	920
16	288	619	907
17	244	578	822
18	197	501	698
19	149	426	575
20	97	389	486
21	67	279	346
22	53	197	250
23	23	114	137
Total	**2384**	**6872**	**9256**

7.5.4 WI: 400026

The last station analyzed in the main body of this thesis is Wisconsin station 400026, shown as WI 1 in Figure 7.13 and Figure 7.14. Like Minnesota station 1335, this station is an example of an outlier station with many days of high percent penetration. Figure 7.22 shows the location of station 400026, and Figure 7.23 depicts the percent penetration calculations for August 8, 2021 along with a visual of the vehicle trajectory points. Table 7.10 shows the hourly percent penetration for August 8, 2021 for station 400026. The hourly percent penetration ranged from 15% at 8am to

52% at 4am. The August 8, 2021 daily percent penetration was 22%, and the August 2021 monthly percent penetration was 18%. This is over 3 times the percent penetration of Wisconsin for August 2021. As with the Minnesota station 1335, the reasoning for the very large percent penetration is unknown. The aggregation of percent penetration over numerous stations helps smooth out these outliers.

The Wisconsin count data was obtained directly from a WisDOT employee via email. Table 7.11 is an example of some of the provided data for station 400026 on August 8, 2021. Like Minnesota, the counts were provided for each direction; therefore, the directional, hourly counts were aggregated before they were compared to the number of connected vehicle journeys.

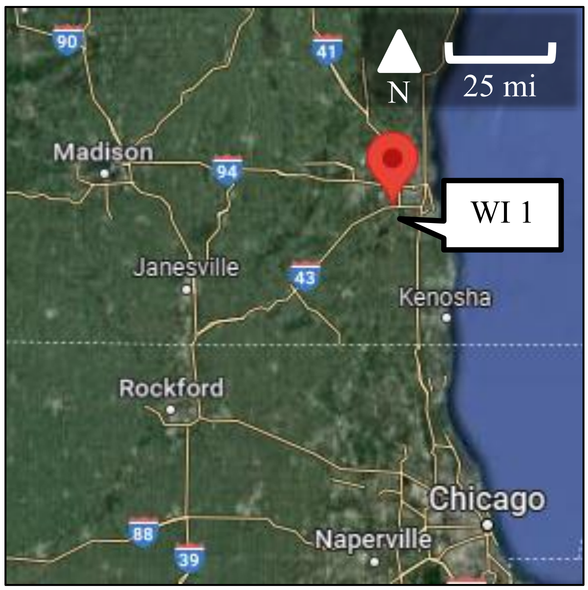


Figure 7.22. Location of Wisconsin station 400026

Date: Aug 8, 2021

Trajectory points: 12565

DOT: 11886

Journeys: 2599

Percent Penetration:

2599 / 11886 = 22%

Figure 7.23. Connected vehicle trajectory points and the associated percent penetration calculations for Wisconsin station 400026

Table 7.10. Percent penetration calculations for August 8, 2021 for Wisconsin station 400026

Date	Hour	DOT Count	CV Count	Percent
8/8/2021	0	109	29	27%
8/8/2021	1	71	17	24%
8/8/2021	2	48	11	23%
8/8/2021	3	43	13	30%
8/8/2021	4	29	15	52%
8/8/2021	5	68	24	35%
8/8/2021	6	185	38	21%
8/8/2021	7	257	61	24%
8/8/2021	8	445	66	15%
8/8/2021	9	602	128	21%
8/8/2021	10	958	233	24%
8/8/2021	11	1079	280	26%
8/8/2021	12	1129	213	19%
8/8/2021	13	1010	198	20%
8/8/2021	14	940	205	22%
8/8/2021	15	961	197	21%
8/8/2021	16	841	218	26%
8/8/2021	17	838	164	20%
8/8/2021	18	670	170	25%
8/8/2021	19	580	86	15%
8/8/2021	20	422	93	22%
8/8/2021	21	279	69	25%
8/8/2021	22	197	41	21%
8/8/2021	23	125	30	24%
8/8/2020	**Total**	**11886**	**2599**	**22%**

Table 7.11. Hourly counts for select hours obtained from WisDOT for August 8, 2021 for Wisconsin station 400026

Date	Hour	Direction	Volume	Total Volume
8/8/2021	0	EB	54	109
8/8/2021	0	WB	55	
8/8/2021	1	EB	28	71
8/8/2021	1	WB	43	
8/8/2021	2	EB	22	48
8/8/2021	2	WB	26	
8/8/2021	3	EB	22	43
8/8/2021	3	WB	21	
8/8/2021	4	EB	12	29
8/8/2021	4	WB	17	
8/8/2021	5	EB	34	68
8/8/2021	5	WB	34	
8/8/2021	6	EB	79	185
8/8/2021	6	WB	106	
8/8/2021	7	EB	127	257
8/8/2021	7	WB	130	
8/8/2021	8	EB	211	445
8/8/2021	8	WB	234	

7.6 Conclusion

The aim of this chapter is to address a common concern of agencies, data representativeness. This chapter details a study that looked at 381 stations across 11 states for two months, August 2020 and August 2021, with an extended fifteen-month analysis for Indiana. Section 6.2 Data describes the station locations, DOT data sources, and the vehicle trajectory data. Section 6.3 Methodology explains the calculation process for determining the hourly, daily, and monthly percent penetration. Sections 6.4, Aggregate Results, and 6.5, Disaggregate Results, provide the resulting percent penetrations. Section 6.4 Aggregate Results focuses on the average percent penetration for entire states over one month, while section 6.5 Disaggregate Results drills down to the percent penetration for individual stations at the hourly, daily, and monthly levels. Additionally, Section 6.5 Disaggregate Results highlights the need to aggregate across hours, days, and even stations in order to smooth out outliers and obtain a reasonable average percent penetration for that particular station or state. Likewise, just as one station's percent penetration doesn't always reflect the state's average, a state's average percent penetration shouldn't be assumed to be the same for all locations across the state.

8. CONCLUSION

This thesis presents a methodology for evaluating intersections for safety improvements utilizing one month of hard-braking data and/or one month of hard-acceleration data. This study compares crash data over a period of 4.5 years (January 2016 to July 2019) at 8 signalized intersections with one month of hard-braking data (July 2019) and one month of hard-acceleration data (July 2019) to determine if there was a statistical relationship between crashes and hard-braking / hard-acceleration events. Graphical illustrations comparing aggregated hard-braking events and crashes (Figure 4.2, Figure 5.3, Figure 5.4, Figure 5.8, and Figure 5.9) demonstrate a visual relationship between the crash and hard-braking / hard-acceleration data sets. A Spearman Rank Order Correlation test was used to evaluate the correlation between crashes and events for several distance ranges, time bins, and crash categories. The statistical tests show that there are strong and very strong correlations between crashes and hard-braking / hard-acceleration events (Table 6.2, Table 6.3, Table 6.4, and Table 6.5). Using a 3-hour time bins, a distance range of 0-1320 ft, and a focus on rear-end collisions, all 8 intersections in the southbound direction had a strong or very strong correlation between hard-braking / hard-acceleration and crashes.

Chapter 7 presents a methodology for assessing the penetration of connected vehicles on roadways. The percent penetration was assessed utilizing DOT and trajectory data from 381 location across 11 states in August 2020 and August 2021. In total, over 1 million hours, 1.7 billion count station records, and 70 million connected vehicle records were analyzed. Figure 7.8 and Figure 7.9 present the percent penetration for each of the states. Penetration ranges from a low of 1.6% in IN at station 990508 to a high of 18% in WI at station 400026 in August 2021.

A longitudinal analysis was performed over fifteen months between July 2019 and February 2022 for Indiana. Figure 7.4 shows the percent penetration for those fifteen months for interstate and non-interstate roads varied from a low of 1.8% in July 2019 to a high of 5.2% in January 2022.

A time of day analysis was performed using August 2021 Indiana data which shows that percent penetration ranged from 2.1% at 1:00 am to 5.3% at 7:00am and remained around 4.5% during the daylight hours (Figure 7.6). The boxpolots, Figure 7.12, Figure 7.13, and Figure 7.14, show the distribution of percent penetrations for hourly, daily, and by station. Finally, several example outlier stations are discussed.

Both the hard-braking and penetrations methodologies presented in this thesis are extremely scalable. Agencies could collect event data, such as hard-braking and hard-acceleration, for a large number of intersections and corridors, and then implement this method to assess all traffic signals within an urban area or an entire state for potential safety issues. Such analysis would be a relatively modest effort, and perhaps more importantly, require no investment in traffic signal infrastructure to collect this performance measure data (Hunter, Saldivar-Carranza, et al., 2021). Additionally, all states have highway performance monitoring systems allowing them to monitor the growth of connected vehicle penetration in their jurisdictions over time. Utilizing this information, agencies should be able to access the value of the connect vehicle data and the aggregation needed to obtain statistically robust performance measures (Hunter, Mathew, Li, et al., 2021).

APPENDIX A: PERCENT PENETRATION DATA REPOSITORY

The purpose of appendix A is to provide additional access to the connected vehicle data and results. Links for a map of the count stations, a file of count station attributes, a folder with DOT count data used, data sources, and the hourly percent penetration calculations are shared. Additionally, data attributes are defined.

<u>Count Stations</u>

Locations:

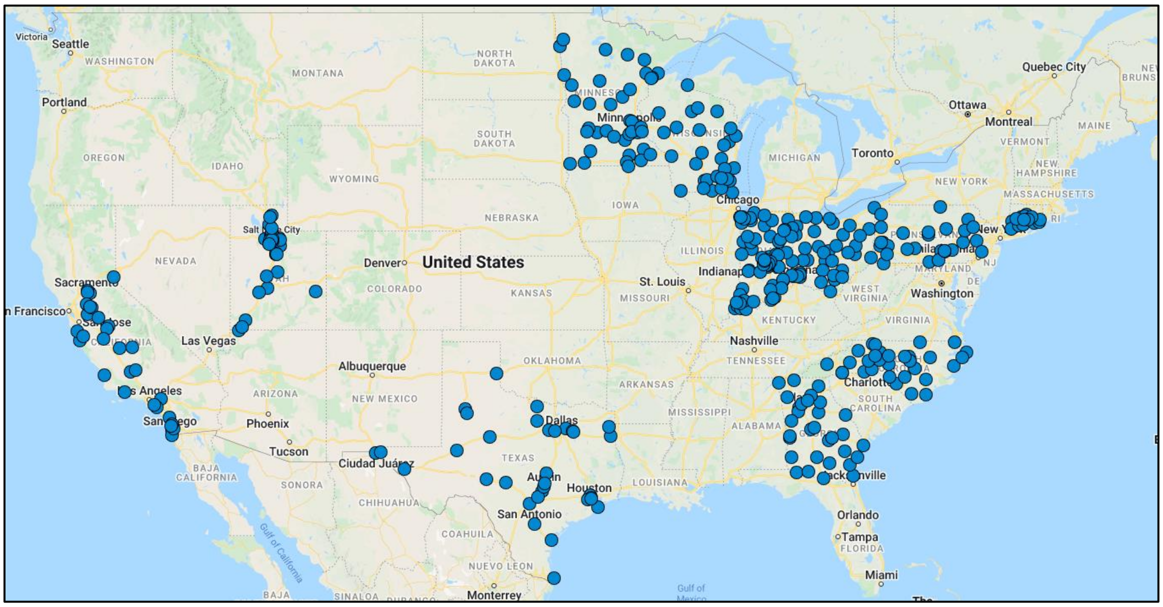


Figure A.1. Location of 381 count station locations

Link to google map: Count Station Map Link

URL: https://www.google.com/maps/d/u/1/edit?mid=1L0SZE4EPqnKcy4cG6qZc3y86V4mjFRW7&usp=sharing

Attributes:

StationID	ActualLat	ActualLong	I/N	R/U	GeofenceMarker1	GeofenceMarker2	RoadWidth	Heading1	Heading2	State
9048	41.6191416	-72.7422769	Non-Interstate	Urban	41.617855755504685, -72.74269762988513	41.620266215717855, -72.74200653077425	115	190	10	CT
9050	41.5837398	-72.3784469	Non-Interstate	Rural	41.586011226015856, -72.38377851468414	41.58830102593479, -72.38752854377387	120	309	129	CT
9051	41.4939704	-72.56933745	Non-Interstate	Urban	41.48971905596023, -72.56662889522367	41.493012933535006, -72.5686355270086	169	155	335	CT
9054	41.501714	-73.151281	Interstate	Urban	41.50175209765923, -73.15114378007364	41.50395800684019, -73.14730688460145	170	232	52	CT
9055	41.4672176	-72.774973	Interstate	Urban	41.46732350855969, -72.77493536377487	41.47080624884021, -72.77359482637353	216	16	196	CT
001-0183	31.83156	-82.08647	Non-Interstate	Rural	31.832617, -82.087411	31.829684932563342, -82.08491203193553	31	144	324	GA
121-5498	33.75879	-84.477	Interstate	Urban	33.759517112647856, -84.4807915201806	33.7588945280971, -84.47650719175627	145	100	279	GA
121-0516	33.5945	-84.49743	Interstate	Urban	33.59132968407183, -84.50299199278227	33.593434362801304, -84.49943538372364	137	54	234	GA
089-3374	33.92031	-84.3041	Interstate	Urban	33.9203102564679, -84.31055523364057	33.9203173666838, -84.30618765763978	163	90	270	GA

Figure A.2. Subset of count station information used

Link: File Link

URL: https://purdue0.sharepoint.com/:x:/s/JTRP/EUD0f5Jpb2JOiOvji4iAE2IBJL0FcWjiDZuw9vBRCre4nA?e=2hgEtt

Attribute Descriptions:

StationID: The ID used by the state to identify the location.

- Utah and California are two exceptions to this rule. Since multiple stationID's correspond to the same roadway location, the stations are identified as UT_# and CA-#. The UT Corresponding Stations and CA Corresponding Stations tabs detail which stations are used for each location.
- Ohio and Minnesota both have a stationID 103. They are differentiated by 103_OH and 103_MN.

ActualLat / ActualLong: The latitude and longitude of the station.

- Due to Utah and California having multiple stations per location, no latitude / longitude is included.

I/N: Identifies station as either located on an interstate or non-interstate.

R/U: Identifies station as either located in a rural or urban setting. If this data was not provided by the state, a judgement was made using satellite imagery.

GeofenceMarker 1 / 2: Latitude and longitude of the boundaries of the geofenced region used to identify the applicable connected vehicle trajectory points.

RoadWidth: Width of the roadway. Used to provide the width of the geofence region.

Heading 1 / 2: The headings of both travel directions. Used to filter out vehicles traveling in the wrong direction (ie. Vehicles traveling over bridges or through underpasses).

State: The state the station is located in.

DOT Traffic Counts:

Data:

Link: Folder Link

URL: https://purdue0.sharepoint.com/:f:/s/JTRP/Em2sVoW9u2NKgb1V6WFqXi0BCZ8arHLoJr9TwY-CDuXKhw?e=7KZwoK

Data Sources:

CA:

- Link: Caltrans PeMS
- URL: https://pems.dot.ca.gov/

CT:

- Provided via email by Kevin Yeomans (email: kevin.yeomans@ct.gov, phone: (860) 594-2090)

GA:

- Link: Traffic Counts in Georgia (drakewell.com)
- URL: https://gdottrafficdata.drakewell.com/publicmultinodemap.asp

IN:

- Link: Traffic Count Database System (TCDS) (ms2soft.com)
- URL: https://indot.public.ms2soft.com/tcds/tsearch.asp?loc=Indot&mod=TCDS

MN:

- Link: TFA ATR Hourly Volume Reports (2002-2017) - TDA, MnDOT (state.mn.us)
- URL: https://www.dot.state.mn.us/traffic/data/reports-hrvol-atr.html

NC:

- Link: Transportation Data Management System (ms2soft.com)
- URL: https://ncdot.public.ms2soft.com/tcds/tsearch.asp?loc=Ncdot&mod=TCDS

OH:

- Link: Transportation Data Management System (ms2soft.com)
- URL: https://odot.public.ms2soft.com/tcds/tsearch.asp?loc=odot

PA:

- Link: Traffic Information Repository (TIRe) | PennDOT
- URL: https://gis.penndot.gov/tire

TX:

- Link: Traffic Count Database System (TCDS) (ms2soft.com)
- URL: https://txdot.public.ms2soft.com/tcds/tsearch.asp?loc=Txdot&mod=TCDS

UT:

- Link: PeMS @ UDOT (iteris-pems.com)
- URL: https://udot.iteris-pems.com/

WI:

- Provided via email by Russell Lewis (email: traffic.counts@dot.wi.gov, phone: (608) 516-5754)

Connected Vehicle Journey Counts:

Data:

Event data from July – August 2019 and trajectory data from July 2019, January 2020, June – September 2020, April 2021 – October 2021, and January – February 2022 used in this study was provided by Wejo Data Services Inc.

Percent Penetration:

Hourly Results:

Station	Date	Hour	DOT Coun	CV Count	Percent	State	I / N	R / U
950106	4/1/2021	0	798	13	0.016	IN	Interstate	Rural
950106	4/2/2021	0	801	22	0.027	IN	Interstate	Rural
950106	4/3/2021	0	738	13	0.018	IN	Interstate	Rural
950106	4/4/2021	0	644	12	0.019	IN	Interstate	Rural
950106	4/17/2021	0	764	9	0.012	IN	Interstate	Rural
950106	4/18/2021	0	645	11	0.017	IN	Interstate	Rural
950106	4/25/2021	0	648	17	0.026	IN	Interstate	Rural
950106	4/5/2021	0	672	15	0.022	IN	Interstate	Rural
950106	4/6/2021	0	702	13	0.019	IN	Interstate	Rural
950106	4/7/2021	0	689	9	0.013	IN	Interstate	Rural
950106	4/8/2021	0	754	10	0.013	IN	Interstate	Rural
950106	4/9/2021	0	749	19	0.025	IN	Interstate	Rural

Figure A.3. Subset of percent penetration hourly results

Link: IN_PercentPenCalcs

URL: https://purdue0.sharepoint.com/:x:/s/JTRP/EVD8gi_JhM1Fkj6jK8tHgjYBc8VCFNHwAfG4332_vUjzTA?e=gOpJ6N

Link: OtherStates_PercentPenCalcs

URL: https://purdue0.sharepoint.com/:x:/s/JTRP/EfiFldzn8YNCuD2l-BEHKxgB3t3uYbCfpIt8XIVF7-puKA?e=dVWlnP

Attributes:

Station: The ID used by the state to identify the location.

- Utah and California are two exceptions to this rule. Since multiple stationID's correspond to the same roadway location, the stations are identified as UT_# and CA-#. The UT Corresponding Stations and CA Corresponding Stations tabs detail which stations are used for each location.
- Ohio and Minnesota both have a stationID 103. They are differentiated by 103_OH and 103_MN.

Date: Day counts occurred

Hour: Hour counts occurred

DOT Count: Number of vehicles reported by the DOT's count station

CV Count: Number of unique connected vehicle journeys

Percent: Percent penetration

$$\% \text{ Penetration} = \frac{\sum Unique\ Trajectories}{DOT\ Volume}$$

State: State station is located in.

I/N: Identifies station as either located on an interstate or non-interstate.

R/U: Identifies station as either located in a rural or urban setting.

APPENDIX B: EXAMPLE STATIONS FOR EACH STATE

Appendix B provides an example station for each state. States are listed in alphabetical order.

California:

Station Name: CA-19 (corresponding Caltrans stations: 1126458, 1126455, 1126470, 1126472)
Latitude: 32.836097
Longitude: -116.962089

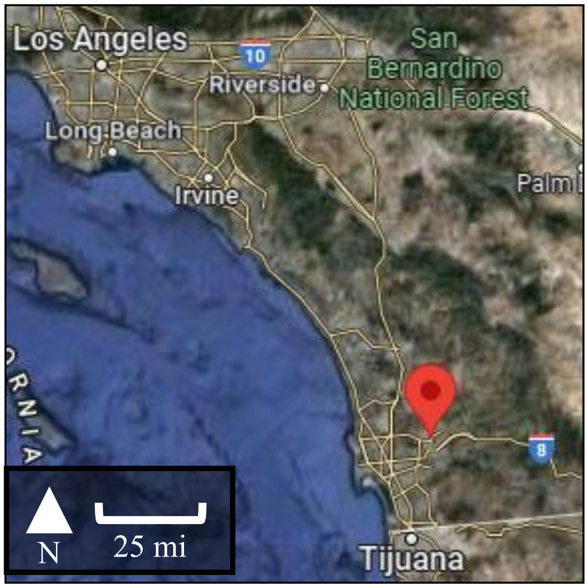
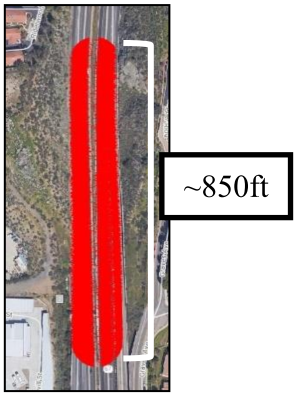
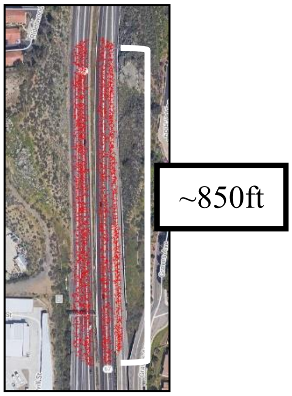


Figure B.1. Location of California station CA-19



Trajectory points: 158,907

(a) August 2020



Trajectory points: 5,798

(b) August 12, 2020

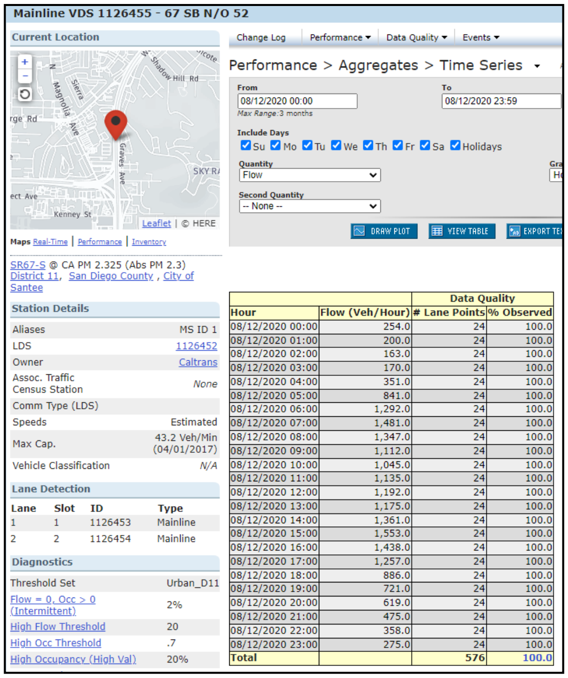
Figure B.2. Connected vehicle points for California station CA-19

Table B.1. DOT Vehicle Counts for August 12, 2020 for California station CA-19

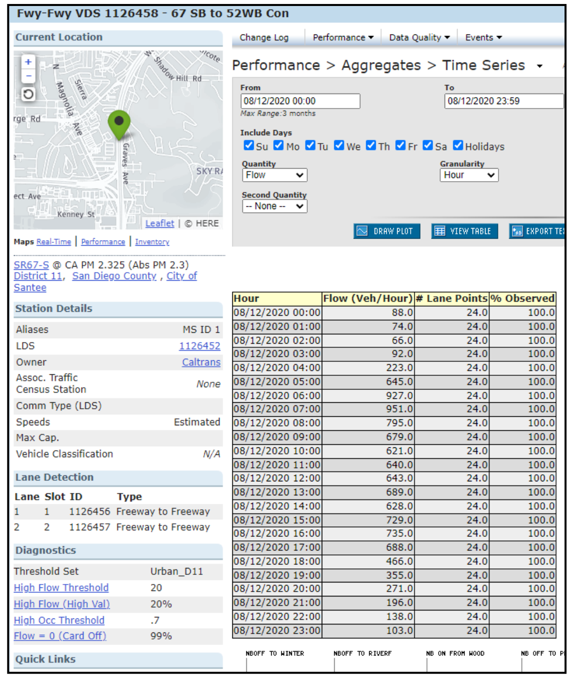
Date	CA-19 Stations				Hour Total
	1126455	**1126458**	**1126470**	**1126472**	
8/12/2020 0:00	254	88	185	83	610
8/12/2020 1:00	200	74	96	50	420
8/12/2020 2:00	163	66	102	43	374
8/12/2020 3:00	170	92	138	42	442
8/12/2020 4:00	351	223	313	88	975
8/12/2020 5:00	841	645	695	225	2406
8/12/2020 6:00	1292	927	1005	421	3645
8/12/2020 7:00	1481	951	1118	496	4046
8/12/2020 8:00	1347	795	983	517	3642
8/12/2020 9:00	1112	679	886	531	3208
8/12/2020 10:00	1045	621	924	624	3214
8/12/2020 11:00	1135	640	1040	747	3562
8/12/2020 12:00	1192	643	1073	815	3723
8/12/2020 13:00	1175	689	1180	850	3894
8/12/2020 14:00	1361	628	1443	1094	4526
8/12/2020 15:00	1553	729	1721	1307	5310
8/12/2020 16:00	1438	735	1698	1514	5385
8/12/2020 17:00	1257	688	1457	1284	4686
8/12/2020 18:00	886	466	1012	799	3163
8/12/2020 19:00	721	355	816	561	2453
8/12/2020 20:00	619	271	710	475	2075
8/12/2020 21:00	475	196	542	288	1501
8/12/2020 22:00	358	138	386	209	1091
8/12/2020 23:00	275	103	294	169	841
Total	**20701**	**11442**	**19817**	**13232**	**65192**

Table B.2. Hourly and resulting daily percent penetration calculations for August 12, 2020 for California station CA-19

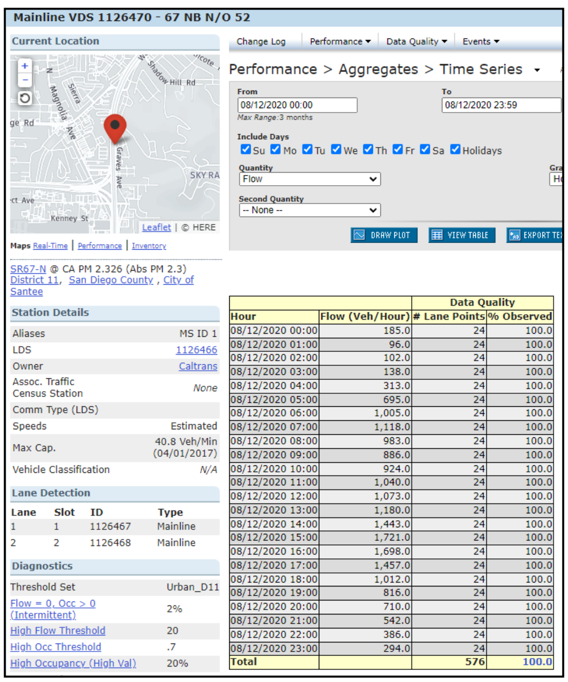
Date	Hour	DOT Count	CV Count	Percent
8/12/2020	0	610	13	2.1%
8/12/2020	1	420	4	1.0%
8/12/2020	2	374	3	0.8%
8/12/2020	3	442	10	2.3%
8/12/2020	4	975	26	2.7%
8/12/2020	5	2406	72	3.0%
8/12/2020	6	3645	104	2.9%
8/12/2020	7	4046	126	3.1%
8/12/2020	8	3642	105	2.9%
8/12/2020	9	3208	88	2.7%
8/12/2020	10	3214	111	3.5%
8/12/2020	11	3562	99	2.8%
8/12/2020	12	3723	122	3.3%
8/12/2020	13	3894	132	3.4%
8/12/2020	14	4526	143	3.2%
8/12/2020	15	5310	161	3.0%
8/12/2020	16	5385	157	2.9%
8/12/2020	17	4686	123	2.6%
8/12/2020	18	3163	92	2.9%
8/12/2020	19	2453	69	2.8%
8/12/2020	20	2075	47	2.3%
8/12/2020	21	1501	40	2.7%
8/12/2020	22	1091	19	1.7%
8/12/2020	23	841	13	1.5%
8/12/2020	**Total**	**65192**	**1879**	**2.9%**



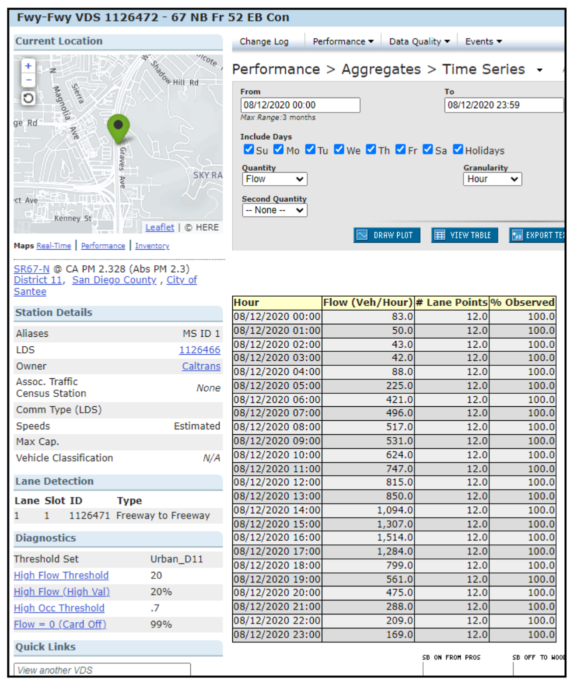
(a) Station 1126455



(b) Station 1126458



(c) Station 1126470



(d) Station 1126472

Figure B.3. Screenshots of California station CA-19 traffic counts for August 12, 2020 from Caltran's PeMS

Connecticut:

Station Name: 009014
Latitude: 41.68763
Longitude: -72.64968

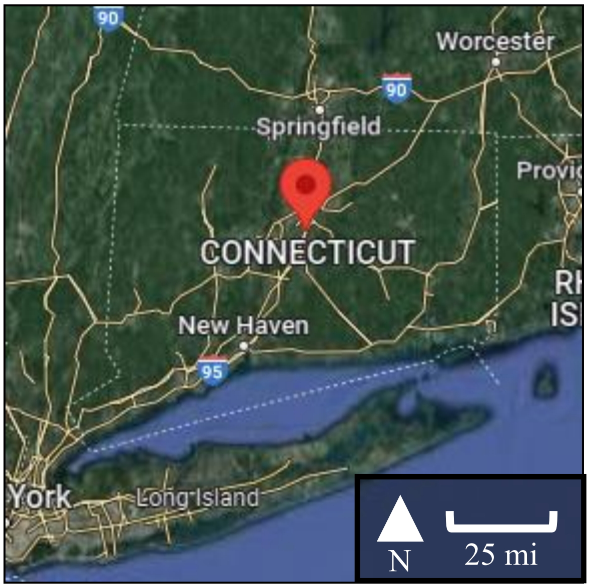
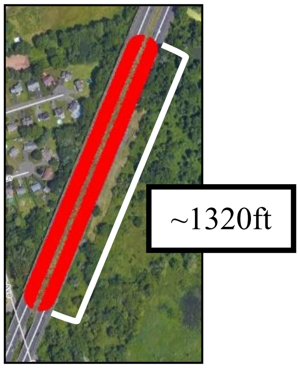
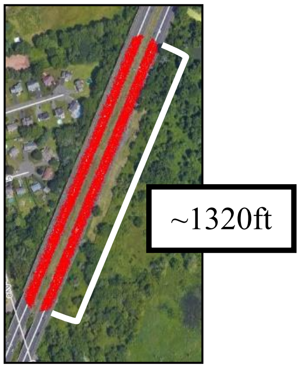


Figure B.4. Location of Connecticut station 009014



Trajectory points: 451,879

(a) August 2020



Trajectory points: 14,757

(b) August 12, 2020

Figure B.5. Connected vehicle points for Connecticut station 009014

Table B.3. DOT vehicle counts for a subset of August 12, 2020 for Connecticut station 009014

Date	Time	Direction	Volume	Total Hour Volume
8/12/2020	12:00 AM	NB	413	643
8/12/2020	12:00 AM	SB	230	
8/12/2020	1:00 AM	NB	412	727
8/12/2020	1:00 AM	SB	315	
8/12/2020	2:00 AM	NB	575	988
8/12/2020	2:00 AM	SB	413	
8/12/2020	3:00 AM	NB	1,088	1930
8/12/2020	3:00 AM	SB	842	
8/12/2020	4:00 AM	NB	3,083	6078
8/12/2020	4:00 AM	SB	2,995	
8/12/2020	5:00 AM	NB	4,669	9697
8/12/2020	5:00 AM	SB	5,028	
8/12/2020	6:00 AM	NB	4,778	9502
8/12/2020	6:00 AM	SB	4,724	
8/12/2020	7:00 AM	NB	3,894	7466
8/12/2020	7:00 AM	SB	3,572	

Table B.4. Hourly and resulting daily percent penetration for calculations for August 12, 2020 for Connecticut station 009014

Date	Hour	DOT Count	CV Count	Percent
8/12/2020	0	643	23	3.6%
8/12/2020	1	727	12	1.7%
8/12/2020	2	988	13	1.3%
8/12/2020	3	1930	17	0.9%
8/12/2020	4	6078	25	0.4%
8/12/2020	5	9697	89	0.9%
8/12/2020	6	9502	168	1.8%
8/12/2020	7	7466	214	2.9%
8/12/2020	8	6880	184	2.7%
8/12/2020	9	7168	176	2.5%
8/12/2020	10	7374	187	2.5%
8/12/2020	11	7643	203	2.7%
8/12/2020	12	8438	205	2.4%
8/12/2020	13	9660	222	2.3%
8/12/2020	14	9803	269	2.7%
8/12/2020	15	10072	268	2.7%
8/12/2020	16	8357	250	3.0%
8/12/2020	17	5706	243	4.3%
8/12/2020	18	3967	157	4.0%
8/12/2020	19	2007	136	6.8%
8/12/2020	20	1711	93	5.4%
8/12/2020	21	1337	68	5.1%
8/12/2020	22	1055	39	3.7%
8/12/2020	23	772	41	5.3%
8/12/2020	**Total**	**128981**	**3302**	**2.6%**

Georgia:

Station Name: 121-5498
Latitude: 33.7595171
Longitude: -84.4807915

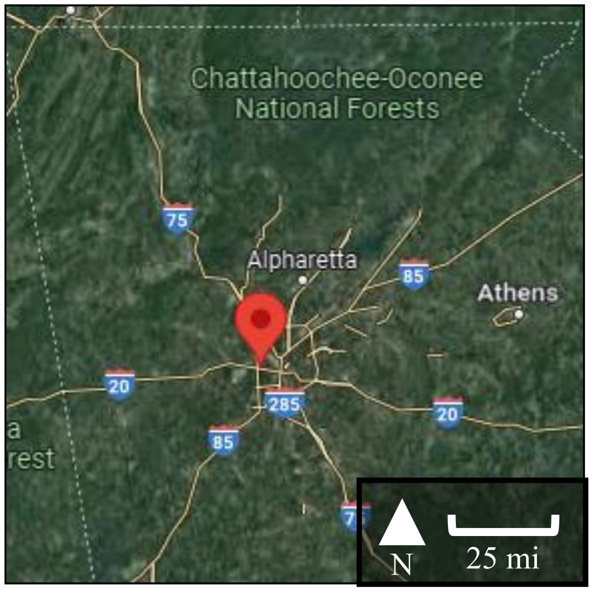
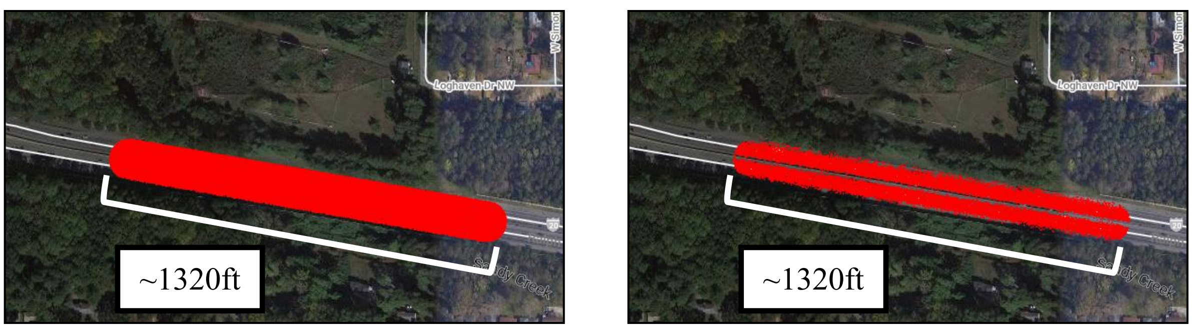


Figure B.6. Location of Georgia station 121-5498



Trajectory points: 692,8677

(a) August 2020

Trajectory points: 22,507

(b) August 12, 2020

Figure B.7. Connected vehicle points for Georgia station 121-5498

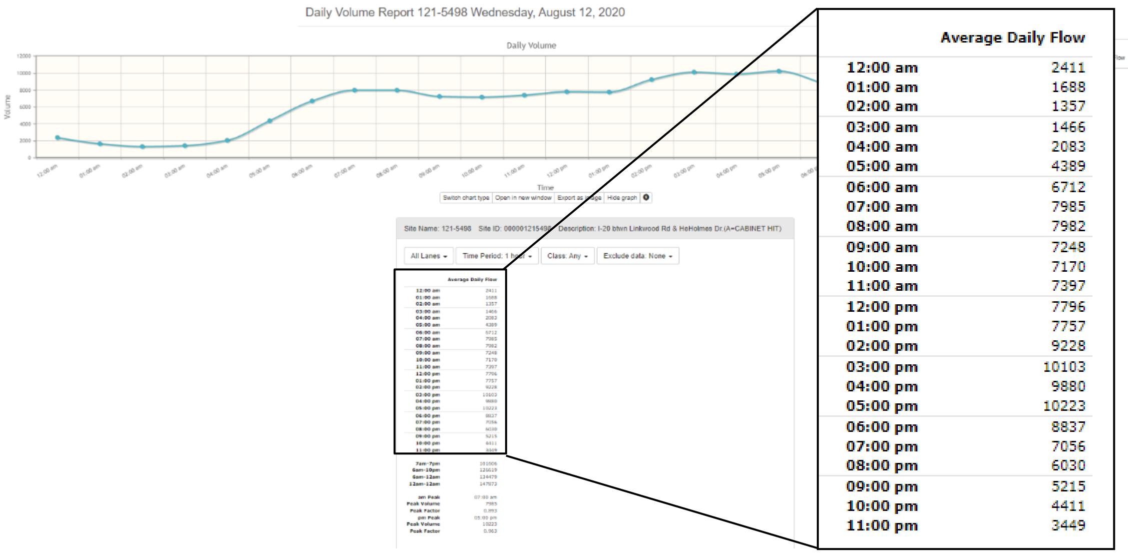


Figure B.8. Screenshot from Georgia's TADA of hourly DOT vehicle counts for August 12, 2020 for Georgia station 121-5498

Table B.5. Hourly and resulting daily percent penetration calculations for August 12, 2020 for Georgia station 121-5498

Date	Hour	DOT Count	CV Count	Percent
8/12/2020	0	2411	67	2.8%
8/12/2020	1	1688	51	3.0%
8/12/2020	2	1357	50	3.7%
8/12/2020	3	1466	41	2.8%
8/12/2020	4	2083	78	3.7%
8/12/2020	5	4389	167	3.8%
8/12/2020	6	6712	227	3.4%
8/12/2020	7	7985	285	3.6%
8/12/2020	8	7982	270	3.4%
8/12/2020	9	7248	259	3.6%
8/12/2020	10	7170	248	3.5%
8/12/2020	11	7397	277	3.7%
8/12/2020	12	7796	293	3.8%
8/12/2020	13	7757	276	3.6%
8/12/2020	14	9228	317	3.4%
8/12/2020	15	10103	316	3.1%
8/12/2020	16	9880	333	3.4%
8/12/2020	17	10223	344	3.4%
8/12/2020	18	8837	275	3.1%
8/12/2020	19	7056	232	3.3%
8/12/2020	20	6030	217	3.6%
8/12/2020	21	5215	155	3.0%
8/12/2020	22	4411	151	3.4%
8/12/2020	23	3449	119	3.5%
8/12/2020	**Total**	**147873**	**5048**	**3.4%**

Indiana:
Station Name: 990311
Latitude: 39.83622
Longitude: -86.23980

Figure B.9. Location of Indiana station 990311

Trajectory points: 329,435

(a) August 2020

Trajectory points: 11,071

(b) August 12, 2020

Figure B.10. Connected vehicle points for Indiana station 990311

Volume Count Report

LOCATION INFO	
Location ID	990311
Type	SPOT
Fnct'l Class	1
Located On	I 65 SB MM 119.7
Loc On Alias	I-65 (INC)
Direction	2-WAY
County	MARION
Community	-
MPO ID	
HPMS ID	
Agency	Indiana DOT

COUNT DATA INFO	
Count Status	Accepted
Start Date	Wed 8/12/2020
End Date	Thu 8/13/2020
Start Time	12:00:00 AM
End Time	12:00:00 AM
Direction	
Notes	
Station	990311
Study	
Speed Limit	
Description	
Sensor Type	
Source	TCDS_COUNT_IMPORT_COMBINE
Latitude,Longitude	

INTERVAL:15-MIN

Time	15-min Interval 1st	2nd	3rd	4th	Hourly Count
0:00-1:00	220	218	191	159	788
1:00-2:00	145	123	161	123	552
2:00-3:00	113	116	114	130	473
3:00-4:00	133	121	133	132	519
4:00-5:00	130	171	226	222	749
5:00-6:00	293	377	521	511	1,702
6:00-7:00	596	786	1,051	849	3,282
7:00-8:00	970	1,176	1,295	1,164	4,605
8:00-9:00	1,039	1,031	1,001	866	3,937
9:00-10:00	862	806	841	778	3,287
10:00-11:00	837	767	777	753	3,134
11:00-12:00	763	790	860	826	3,239
12:00-13:00	833	903	810	867	3,413
13:00-14:00	862	931	879	857	3,529
14:00-15:00	903	974	1,140	1,065	4,082
15:00-16:00	1,102	1,107	1,248	1,272	4,729
16:00-17:00	1,298	1,444	1,429	1,349	5,520
17:00-18:00	1,527	1,378	1,250	1,117	5,272
18:00-19:00	1,019	917	908	782	3,626
19:00-20:00	735	712	693	588	2,728
20:00-21:00	626	559	489	511	2,185
21:00-22:00	507	470	444	414	1,835
22:00-23:00	391	337	314	291	1,333
23:00-24:00	256	275	264	211	1,006
Total					65,525
AADT					57,269
AM Peak					07:15-08:15 4,674
PM Peak					16:15-17:15 5,749

Figure B.11. Screenshot from Indiana's TCDS of hourly DOT vehicle counts for August 12, 2020 for Indiana station 990311

Table B.6. Hourly and resulting daily percent penetration for calculations for August 12, 2020 for Indiana station 990311

Date	Hour	DOT Count	CV Count	Percent
8/12/2020	0	788	21	2.7%
8/12/2020	1	552	10	1.8%
8/12/2020	2	473	7	1.5%
8/12/2020	3	519	12	2.3%
8/12/2020	4	749	21	2.8%
8/12/2020	5	1702	49	2.9%
8/12/2020	6	3282	136	4.1%
8/12/2020	7	4605	166	3.6%
8/12/2020	8	3937	130	3.3%
8/12/2020	9	3287	124	3.8%
8/12/2020	10	3134	106	3.4%
8/12/2020	11	3239	121	3.7%
8/12/2020	12	3413	139	4.1%
8/12/2020	13	3529	164	4.6%
8/12/2020	14	4082	154	3.8%
8/12/2020	15	4729	192	4.1%
8/12/2020	16	5520	207	3.8%
8/12/2020	17	5272	185	3.5%
8/12/2020	18	3626	147	4.1%
8/12/2020	19	2728	102	3.7%
8/12/2020	20	2185	91	4.2%
8/12/2020	21	1835	80	4.4%
8/12/2020	22	1333	51	3.8%
8/12/2020	23	1006	32	3.2%
8/12/2020	**Total**	**65525**	**2447**	**3.7%**

Minnesota:

Station Name: 384
Latitude: 45.0362
Longitude: -92.8392

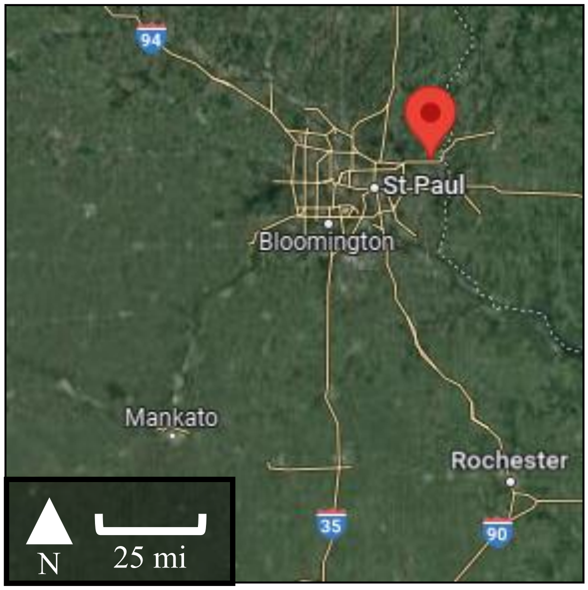
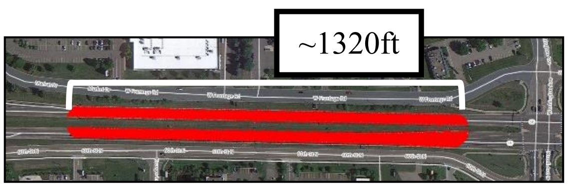
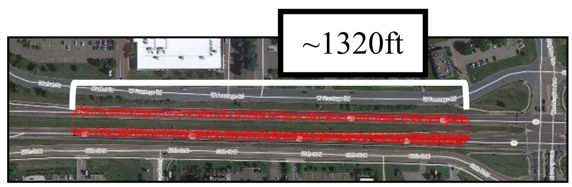


Figure B.12. Location of Minnesota station 384



Trajectory points: 482,418

(a) August 2020



Trajectory points: 15,068

(b) August 12, 2020

Figure B.13. Connected vehicle points for Minnesota station 384

Table B.7. DOT vehicle counts for August 12, 2020 for Minnesota station 384

Direction	**EB**	**EB**	**WB**	**WB**	**Total**
Lane #	1	2	1	2	
Hour					
0	49	17	70	18	154
1	46	16	107	47	216
2	39	16	49	11	115
3	60	14	58	9	141
4	110	54	178	88	430
5	228	141	420	452	1241
6	364	298	580	800	2042
7	508	536	622	631	2297
8	558	525	557	509	2149
9	623	552	553	436	2164
10	633	555	615	481	2284
11	709	563	653	490	2415
12	749	597	685	564	2595
13	746	691	663	514	2614
14	770	773	689	589	2821
15	822	884	749	614	3069
16	885	913	761	597	3156
17	790	776	695	536	2797
18	587	499	533	376	1995
19	419	340	411	256	1426
20	315	232	346	231	1124
21	262	177	283	163	885
22	151	108	188	119	566
23	102	48	116	65	331

Table B.8. Hourly and resulting daily percent penetration calculations for August 12, 2020 for Minnesota station 384

Date	Hour	DOT Count	CV Count	Percent
8/12/2020	0	154	5	3.2%
8/12/2020	1	216	6	2.8%
8/12/2020	2	115	1	0.9%
8/12/2020	3	141	8	5.7%
8/12/2020	4	430	27	6.3%
8/12/2020	5	1241	81	6.5%
8/12/2020	6	2042	114	5.6%
8/12/2020	7	2297	144	6.3%
8/12/2020	8	2149	130	6.0%
8/12/2020	9	2164	120	5.5%
8/12/2020	10	2284	101	4.4%
8/12/2020	11	2415	136	5.6%
8/12/2020	12	2595	136	5.2%
8/12/2020	13	2614	133	5.1%
8/12/2020	14	2821	160	5.7%
8/12/2020	15	3069	180	5.9%
8/12/2020	16	3156	180	5.7%
8/12/2020	17	2797	161	5.8%
8/12/2020	18	1995	100	5.0%
8/12/2020	19	1426	84	5.9%
8/12/2020	20	1124	61	5.4%
8/12/2020	21	885	46	5.2%
8/12/2020	22	566	30	5.3%
8/12/2020	23	331	17	5.1%
8/12/2020	**Total**	**39027**	**2161**	**5.5%**

North Carolina:

Station Name: 0920000016
Latitude: 35.7538352
Longitude: -78.6850245

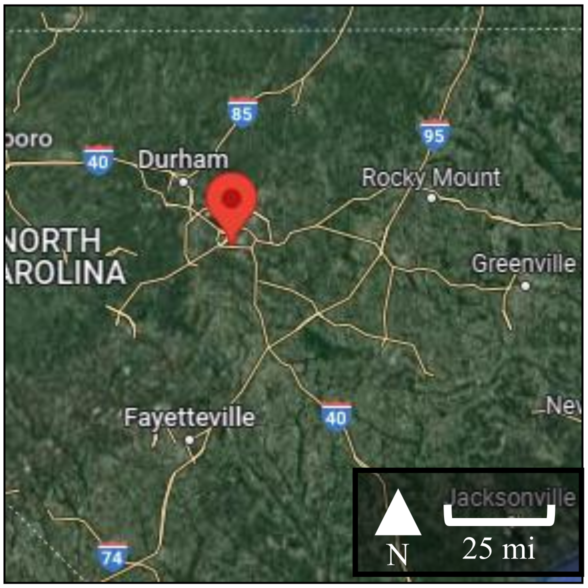
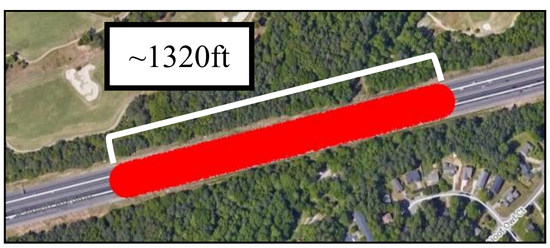
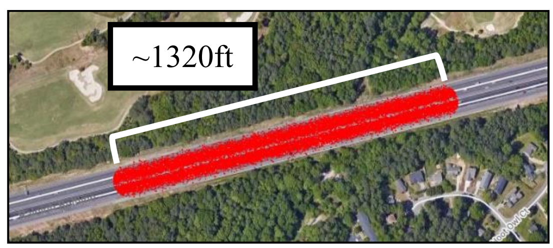


Figure B.14. Location of North Carolina station 0920000016



Trajectory points: 528,014

(a) August 2020



Trajectory points: 17,476

(b) August 12, 2020

Figure B.15. Connected vehicle points for North Carolina station 0920000016

Volume Count Report

LOCATION INFO	
Location ID	0920000016
Type	SPOT
Fnct'l Class	1
Located On	I 40
Loc On Alias	
EAST OF	SR 1571 GORMAN ST (EXIT 295)
Direction	2-WAY
County	Wake
Community	-
MPO ID	
HPMS ID	
Agency	NCDOT

COUNT DATA INFO	
Count Status	Atypical
Start Date	Wed 8/12/2020
End Date	Thu 8/13/2020
Start Time	12:00:00 AM
End Time	12:00:00 AM
Direction	2-WAY
Notes	
Station	
Study	
Speed Limit	
Description	
Sensor Type	Loop
Source	CombineVolumeCountsIncremental
Latitude,Longitude	

INTERVAL:15-MIN

Time	15-min Interval				Hourly Count
	1st	2nd	3rd	4th	
0:00-1:00	256	246	214	213	929
1:00-2:00	147	147	143	116	553
2:00-3:00	117	134	150	156	557
3:00-4:00	143	160	179	203	685
4:00-5:00	228	266	380	356	1,230
5:00-6:00	507	712	874	1,006	3,099
6:00-7:00	1,352	1,900	2,128	2,169	7,549
7:00-8:00	2,035	2,196	2,411	2,308	8,950
8:00-9:00	2,011	1,990	2,082	1,977	8,060
9:00-10:00	1,816	1,758	1,885	1,823	7,282
10:00-11:00	1,743	1,744	1,755	1,734	6,976
11:00-12:00	1,685	1,697	1,771	1,734	6,887
12:00-13:00	1,781	1,767	1,848	1,815	7,211
13:00-14:00	1,874	1,809	1,803	1,904	7,390
14:00-15:00	1,908	1,992	1,959	2,022	7,881
15:00-16:00	2,009	2,156	2,227	2,355	8,747
16:00-17:00	2,401	2,464	2,447	2,414	9,726
17:00-18:00	2,306	2,525	2,593	2,444	9,868
18:00-19:00	2,101	2,002	1,782	1,593	7,478
19:00-20:00	1,569	1,476	1,289	1,193	5,527
20:00-21:00	1,162	1,019	1,031	917	4,129
21:00-22:00	841	812	705	653	3,011
22:00-23:00	677	607	561	466	2,311
23:00-24:00	411	417	337	306	1,471
Total					127,507
AM Peak	07:00-08:00 8,950				
PM Peak	17:00-18:00 9,868				

Figure B.16. Screenshot from North Carolina's TCMS of hourly DOT vehicle counts for August 12, 2020 for North Carolina station 0920000016

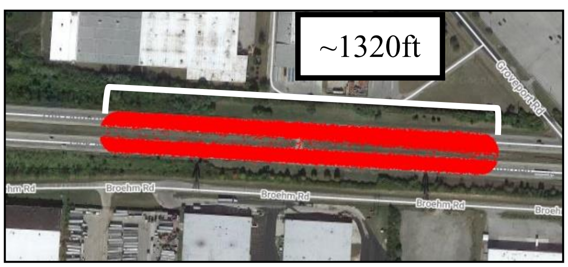
Table B.9. Hourly and resulting daily percent penetration calculations for August 12, 2020 for North Carolina station 0920000016

Date	Hour	DOT Count	CV Count	Percent
8/12/2020	0	929	13	1.4%
8/12/2020	1	553	8	1.4%
8/12/2020	2	557	8	1.4%
8/12/2020	3	685	17	2.5%
8/12/2020	4	1230	40	3.3%
8/12/2020	5	3099	91	2.9%
8/12/2020	6	7549	209	2.8%
8/12/2020	7	8950	288	3.2%
8/12/2020	8	8060	245	3.0%
8/12/2020	9	7282	234	3.2%
8/12/2020	10	6976	186	2.7%
8/12/2020	11	6887	254	3.7%
8/12/2020	12	7211	273	3.8%
8/12/2020	13	7390	253	3.4%
8/12/2020	14	7881	246	3.1%
8/12/2020	15	8747	274	3.1%
8/12/2020	16	9726	323	3.3%
8/12/2020	17	9868	293	3.0%
8/12/2020	18	7478	206	2.8%
8/12/2020	19	5527	136	2.5%
8/12/2020	20	4129	102	2.5%
8/12/2020	21	3011	55	1.8%
8/12/2020	22	2311	47	2.0%
8/12/2020	23	1471	35	2.4%
8/12/2020	**Total**	**127507**	**3836**	**3.0%**

Ohio:

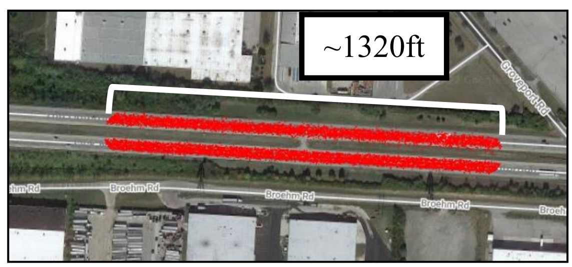
Station Name: 119025
Latitude: 39.8717352
Longitude: -82.9477232

Figure B.17. Location of Ohio station 119025



Trajectory points: 328,328

(a) August 2020



Trajectory points: 11,469

(b) August 12, 2020

Figure B.18. Connected vehicle points for Ohio station 119025

Volume Count Report

LOCATION INFO	
Location ID	119025
Type	SPOT
Fnct'l Class	1
Located On	JACK NICKLAUS FWY
Loc On Alias	N97
Direction	2-WAY
County	FRANKLIN
Community	OBETZ
MPO ID	
HPMS ID	
Agency	ODOT

COUNT DATA INFO	
Count Status	Accepted
Start Date	Wed 8/12/2020
End Date	Thu 8/13/2020
Start Time	12:00:00 AM
End Time	12:00:00 AM
Direction	
Notes	
Station	
Study	
Speed Limit	
Description	
Sensor Type	ATR
Source	TCDS_COUNT_IMPORT_COMBINE
Latitude,Longitude	

INTERVAL:15-MIN

Time	15-min Interval				Hourly Count
	1st	2nd	3rd	4th	
0:00-1:00	204	206	177	173	760
1:00-2:00	128	143	155	179	605
2:00-3:00	118	175	127	120	540
3:00-4:00	132	148	142	189	611
4:00-5:00	170	209	266	324	969
5:00-6:00	363	445	667	784	2,259
6:00-7:00	698	883	1,084	1,280	3,945
7:00-8:00	990	1,123	1,174	1,334	4,621
8:00-9:00	1,188	1,031	1,053	1,020	4,292
9:00-10:00	940	915	923	957	3,735
10:00-11:00	819	894	883	906	3,502
11:00-12:00	907	973	945	962	3,787
12:00-13:00	942	940	965	952	3,799
13:00-14:00	937	1,016	955	1,105	4,013
14:00-15:00	1,055	1,137	1,175	1,344	4,711
15:00-16:00	1,278	1,441	1,342	1,440	5,501
16:00-17:00	1,248	1,522	1,411	1,464	5,645
17:00-18:00	1,257	1,373	1,302	1,264	5,196
18:00-19:00	1,037	953	808	790	3,588
19:00-20:00	708	722	692	612	2,734
20:00-21:00	603	572	541	508	2,224
21:00-22:00	462	457	439	418	1,776
22:00-23:00	386	428	333	307	1,454
23:00-24:00	304	314	266	284	1,168
Total					71,435
AADT					61,434
AM Peak					07:15-08:15 4,819
PM Peak					16:15-17:15 5,654

Figure B.19. Screenshot from Ohio's TCMS of hourly DOT vehicle counts for August 12, 2020 for Ohio station 119025

Table B.10. Hourly and resulting daily percent penetration calculations for August 12, 2020 for Ohio station 119025

Date	Hour	DOT Count	CV Count	Percent
8/12/2020	0	760	15	2.0%
8/12/2020	1	605	11	1.8%
8/12/2020	2	540	12	2.2%
8/12/2020	3	611	5	0.8%
8/12/2020	4	969	23	2.4%
8/12/2020	5	2259	71	3.1%
8/12/2020	6	3945	153	3.9%
8/12/2020	7	4621	167	3.6%
8/12/2020	8	4292	139	3.2%
8/12/2020	9	3735	123	3.3%
8/12/2020	10	3502	115	3.3%
8/12/2020	11	3787	108	2.9%
8/12/2020	12	3799	127	3.3%
8/12/2020	13	4013	155	3.9%
8/12/2020	14	4711	158	3.4%
8/12/2020	15	5501	201	3.7%
8/12/2020	16	5645	219	3.9%
8/12/2020	17	5196	200	3.8%
8/12/2020	18	3588	117	3.3%
8/12/2020	19	2734	98	3.6%
8/12/2020	20	2224	84	3.8%
8/12/2020	21	1776	54	3.0%
8/12/2020	22	1454	57	3.9%
8/12/2020	23	1168	21	1.8%
8/12/2020	**Total**	**71435**	**2433**	**3.4%**

Pennsylvania:

Station Name: 1623
Latitude: 40.2580
Longitude: -77.0647

Figure B.20. Location of Pennsylvania station 1623

Trajectory points: 167,390

(a) August 2020

Trajectory points: 8,091

(b) August 12, 2020

Figure B.21. Connected vehicle points for Pennsylvania station 1623

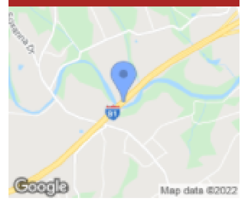
TMS Site 1623: Traffic Monitoring Report

Location Description: 1.4 mi. S of PA 114 (Silver Spring)

Details	
Type of Count	CONTINUOUS CLASS
Type of Site	CAVC (831)
Schedule	CONTINUOUS
Duration	CONTINUOUS
Frequency Cycle	01
Cycle Year	01

Location	
County	CUMBERLAND (21)
Route	0081
Segment	0554
Offset	0000
Latitude	40.2576
Longitude	-77.08499

Map



Traffic Data

Timeframe: All Years / 2020 / Aug 12, 2020*

Hourly Traffic for Aug 12, 2020

Direction: Both Directions / North , South

Show All Classes: ☐

Hour	Volume	Trucks	Truck %	Volume Graph
12:00 AM	1,041	630	60.5	
01:00 AM	767	486	63.4	
02:00 AM	821	538	65.5	
03:00 AM	1,048	629	60	
04:00 AM	1,442	740	51.3	
05:00 AM	2,404	887	36.9	
06:00 AM	3,523	1,117	31.7	
07:00 AM	4,021	1,246	31	
08:00 AM	3,676	1,331	36.2	
09:00 AM	3,754	1,513	40.3	
10:00 AM	3,743	1,427	38.1	
11:00 AM	3,921	1,495	38.1	
12:00 PM	4,113	1,554	37.8	
01:00 PM	4,262	1,507	35.4	
02:00 PM	4,790	1,509	31.5	
03:00 PM	5,162	1,443	28	
04:00 PM	4,836	1,337	27.6	
05:00 PM	4,524	1,312	29	
06:00 PM	3,422	1,169	34.2	
07:00 PM	2,616	987	37.7	
08:00 PM	2,227	865	38.8	
09:00 PM	1,729	766	44.3	
10:00 PM	1,567	696	44.4	
11:00 PM	1,316	649	49.3	

⚠ Note: Traffic volumes and classification breakdowns may be lower than normal due to the COVID-19 pandemic.

Figure B.22. Screenshot from Pennsylvania's TIRe of hourly DOT vehicle counts for August 12, 2020 for Pennsylvania station 1623

Table B.11. Hourly and resulting daily percent penetration calculations for August 12, 2020 for Pennsylvania station 1623

Date	Hour	DOT Count	CV Count	Percent
8/12/2020	0	1041	7	0.7%
8/12/2020	1	767	13	1.7%
8/12/2020	2	821	8	1.0%
8/12/2020	3	1048	14	1.3%
8/12/2020	4	1442	18	1.2%
8/12/2020	5	2404	36	1.5%
8/12/2020	6	3523	72	2.0%
8/12/2020	7	4021	114	2.8%
8/12/2020	8	3676	84	2.3%
8/12/2020	9	3754	94	2.5%
8/12/2020	10	3743	104	2.8%
8/12/2020	11	3921	114	2.9%
8/12/2020	12	4113	98	2.4%
8/12/2020	13	4262	119	2.8%
8/12/2020	14	4790	128	2.7%
8/12/2020	15	5162	137	2.7%
8/12/2020	16	4836	146	3.0%
8/12/2020	17	4524	122	2.7%
8/12/2020	18	3422	87	2.5%
8/12/2020	19	2616	61	2.3%
8/12/2020	20	2227	51	2.3%
8/12/2020	21	1729	29	1.7%
8/12/2020	22	1567	22	1.4%
8/12/2020	23	1316	30	2.3%
8/12/2020	**Total**	**70725**	**1708**	**2.4%**

Texas:

Station Name: A193
Latitude: 32.783549
Longitude: -97.466786

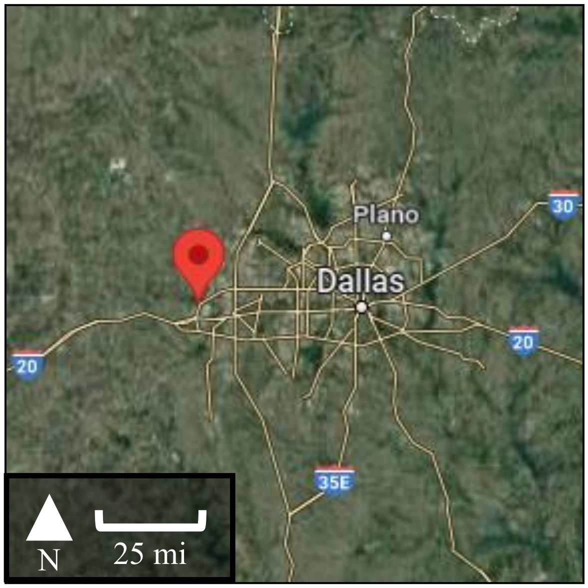
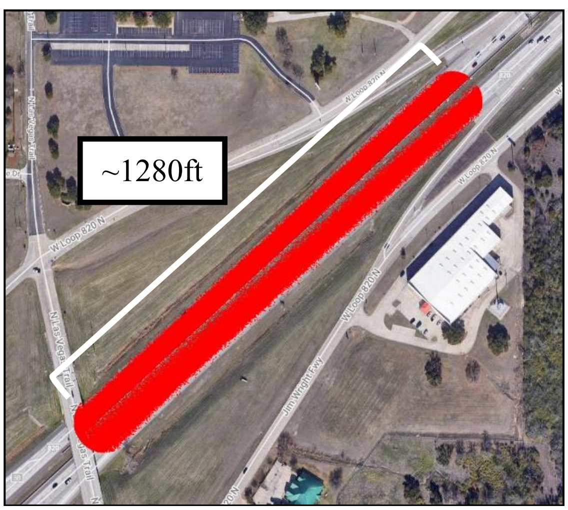
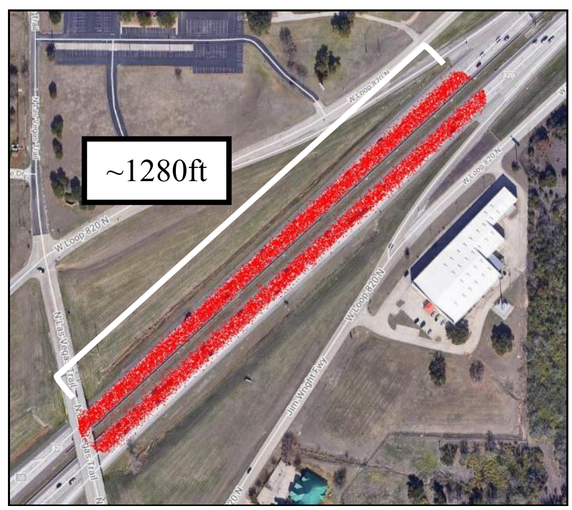


Figure B.23. Location of Texas location A193



Trajectory points: 660,869

(a) August 2020



Trajectory points: 22,339

(b) August 12, 2020

Figure B.24. Connected vehicle points for Texas location A193

LOCATION INFO	
Location ID	A193
Type	SPOT
Fnct'l Class	1
Located On	IH0820
Loc On Alias	IH0820-KG
Direction	2-WAY
County	Tarrant
Community	Fort Worth
MPO ID	
HPMS ID	UNASSIGNED
Agency	Texas DOT

COUNT DATA INFO	
Count Status	Accepted
Start Date	Wed 8/12/2020
End Date	Thu 8/13/2020
Start Time	12:00:00 AM
End Time	12:00:00 AM
Direction	
Notes	
Station	
Study	
Speed Limit	
Description	
Sensor Type	ATR
Source	TCDS_COUNT_IMPORT_COMBINE
Latitude,Longitude	

INTERVAL:60-MIN	
Time	Hourly Count
0:00-1:00	961
1:00-2:00	555
2:00-3:00	526
3:00-4:00	621
4:00-5:00	1,123
5:00-6:00	3,004
6:00-7:00	5,069
7:00-8:00	6,481
8:00-9:00	5,752
9:00-10:00	4,808
10:00-11:00	4,963
11:00-12:00	4,870
12:00-13:00	5,362
13:00-14:00	5,497
14:00-15:00	5,989
15:00-16:00	6,624
16:00-17:00	7,968
17:00-18:00	7,996
18:00-19:00	5,884
19:00-20:00	4,383
20:00-21:00	3,290
21:00-22:00	2,705
22:00-23:00	1,810
23:00-24:00	1,220
Total	97,461
AADT	95,219
AM Peak	07:00-08:00 6,481
PM Peak	17:00-18:00 7,996

Figure B.25. Screenshot from Texas's TCDS of hourly DOT vehicle counts for August 12, 2020 for Texas station A193

Table B.12. Hourly and resulting daily percent penetration calculations for August 12, 2020 for Texas station A193

Date	Hour	DOT Count	CV Count	Percent
8/12/2020	0	961	28	2.9%
8/12/2020	1	555	15	2.7%
8/12/2020	2	526	15	2.9%
8/12/2020	3	621	26	4.2%
8/12/2020	4	1123	51	4.5%
8/12/2020	5	3004	136	4.5%
8/12/2020	6	5069	254	5.0%
8/12/2020	7	6481	349	5.4%
8/12/2020	8	5752	320	5.6%
8/12/2020	9	4808	268	5.6%
8/12/2020	10	4963	280	5.6%
8/12/2020	11	4870	277	5.7%
8/12/2020	12	5362	321	6.0%
8/12/2020	13	5497	306	5.6%
8/12/2020	14	5989	311	5.2%
8/12/2020	15	6624	384	5.8%
8/12/2020	16	7968	423	5.3%
8/12/2020	17	7996	402	5.0%
8/12/2020	18	5884	323	5.5%
8/12/2020	19	4383	203	4.6%
8/12/2020	20	3290	152	4.6%
8/12/2020	21	2705	120	4.4%
8/12/2020	22	1810	58	3.2%
8/12/2020	23	1220	33	2.7%
8/12/2020	Total	97,461	5,055	5.2%

Utah:

Station Name: UT_14 (corresponding UDOT stations: 755, 758, 99755, 99758)
Latitude: 40.949177
Longitude: -111.891273

Figure B.26. Location of Utah station UT_14

Trajectory points: 530,965

(a) August 2020

Trajectory points: 18,478

(b) August 12, 2020

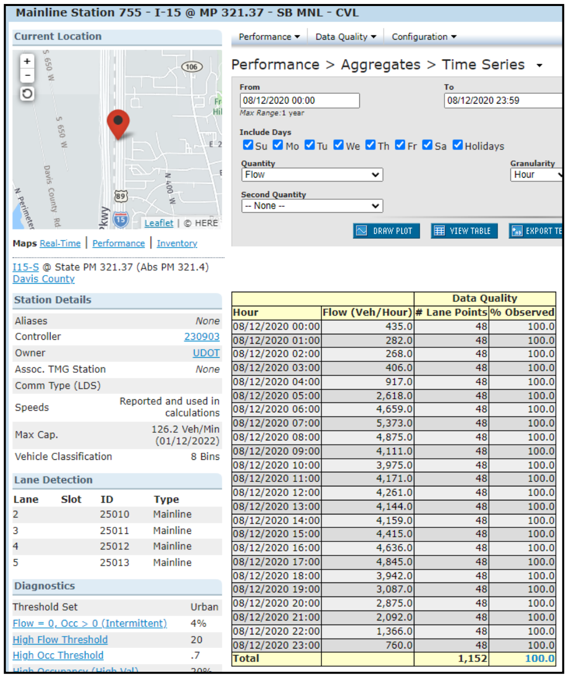
Figure B.27. Connected vehicle points for Utah station UT_14

Table B.13. DOT vehicle counts for August 12, 2020, for Utah station UT_14

Date	UT_14 Stations				Hour Total
	755	**758**	**99755**	**99758**	
8/18/2020 0:00	435	573	14	5	1027
8/18/2020 1:00	282	362	12	5	661
8/18/2020 2:00	268	282	9	1	560
8/18/2020 3:00	406	254	10	0	670
8/18/2020 4:00	917	458	35	4	1414
8/18/2020 5:00	2618	1148	269	21	4056
8/18/2020 6:00	4659	2302	585	78	7624
8/18/2020 7:00	5373	3256	555	117	9301
8/18/2020 8:00	4875	3612	561	184	9232
8/18/2020 9:00	4111	3725	450	239	8525
8/18/2020 10:00	3975	4098	522	370	8965
8/18/2020 11:00	4171	4309	502	315	9297
8/18/2020 12:00	4261	4377	509	303	9450
8/18/2020 13:00	4144	4657	481	337	9619
8/18/2020 14:00	4159	5026	577	421	10183
8/18/2020 15:00	4415	5886	594	567	11462
8/18/2020 16:00	4636	6129	617	725	12107
8/18/2020 17:00	4845	6240	686	568	12339
8/18/2020 18:00	3942	4922	541	383	9788
8/18/2020 19:00	3087	3538	371	210	7206
8/18/2020 20:00	2875	2949	340	167	6331
8/18/2020 21:00	2092	2374	309	135	4910
8/18/2020 22:00	1366	1695	137	84	3282
8/18/2020 23:00	760	1022	46	32	1860
Total	**72672**	**73194**	**8732**	**5271**	**159869**

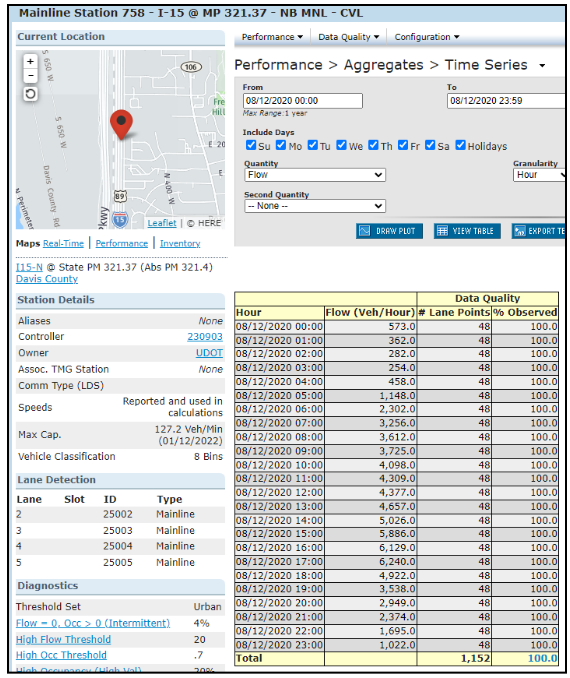
Table B.14. Hourly and resulting daily percent penetration calculations for August 12, 2020 for Utah station UT_14

Date	Hour	DOT Count	CV Count	Percent
8/12/2020	0	1027	17	1.7%
8/12/2020	1	661	8	1.2%
8/12/2020	2	560	12	2.1%
8/12/2020	3	670	7	1.0%
8/12/2020	4	1414	30	2.1%
8/12/2020	5	4056	103	2.5%
8/12/2020	6	7624	224	2.9%
8/12/2020	7	9301	266	2.9%
8/12/2020	8	9232	239	2.6%
8/12/2020	9	8525	237	2.8%
8/12/2020	10	8965	267	3.0%
8/12/2020	11	9297	289	3.1%
8/12/2020	12	9450	267	2.8%
8/12/2020	13	9619	273	2.8%
8/12/2020	14	10183	267	2.6%
8/12/2020	15	11462	316	2.8%
8/12/2020	16	12107	295	2.4%
8/12/2020	17	12339	328	2.7%
8/12/2020	18	9788	241	2.5%
8/12/2020	19	7206	171	2.4%
8/12/2020	20	6331	130	2.1%
8/12/2020	21	4910	96	2.0%
8/12/2020	22	3282	61	1.9%
8/12/2020	23	1860	36	1.9%
8/12/2020	**Total**	**159869**	**4180**	**2.6%**



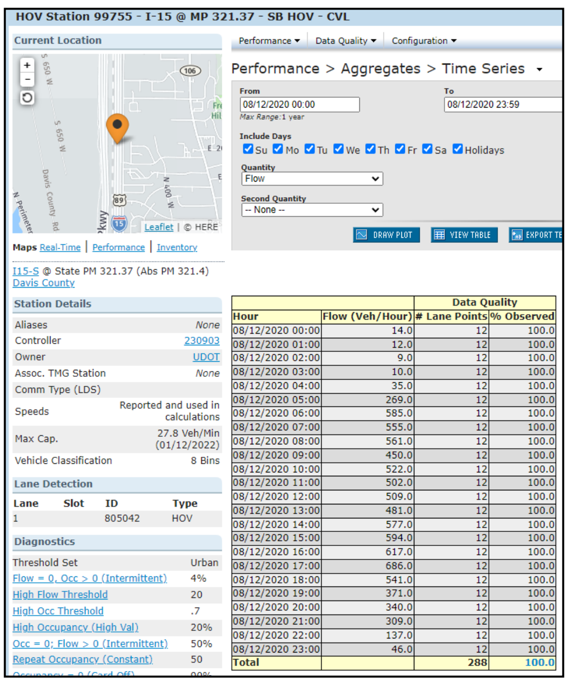
Hour	Flow (Veh/Hour)	Data Quality: # Lane Points	Data Quality: % Observed
08/12/2020 00:00	435.0	48	100.0
08/12/2020 01:00	282.0	48	100.0
08/12/2020 02:00	268.0	48	100.0
08/12/2020 03:00	406.0	48	100.0
08/12/2020 04:00	917.0	48	100.0
08/12/2020 05:00	2,618.0	48	100.0
08/12/2020 06:00	4,659.0	48	100.0
08/12/2020 07:00	5,373.0	48	100.0
08/12/2020 08:00	4,875.0	48	100.0
08/12/2020 09:00	4,111.0	48	100.0
08/12/2020 10:00	3,975.0	48	100.0
08/12/2020 11:00	4,171.0	48	100.0
08/12/2020 12:00	4,261.0	48	100.0
08/12/2020 13:00	4,144.0	48	100.0
08/12/2020 14:00	4,159.0	48	100.0
08/12/2020 15:00	4,415.0	48	100.0
08/12/2020 16:00	4,636.0	48	100.0
08/12/2020 17:00	4,845.0	48	100.0
08/12/2020 18:00	3,942.0	48	100.0
08/12/2020 19:00	3,087.0	48	100.0
08/12/2020 20:00	2,875.0	48	100.0
08/12/2020 21:00	2,092.0	48	100.0
08/12/2020 22:00	1,366.0	48	100.0
08/12/2020 23:00	760.0	48	100.0
Total		1,152	100.0

(a) Station 755



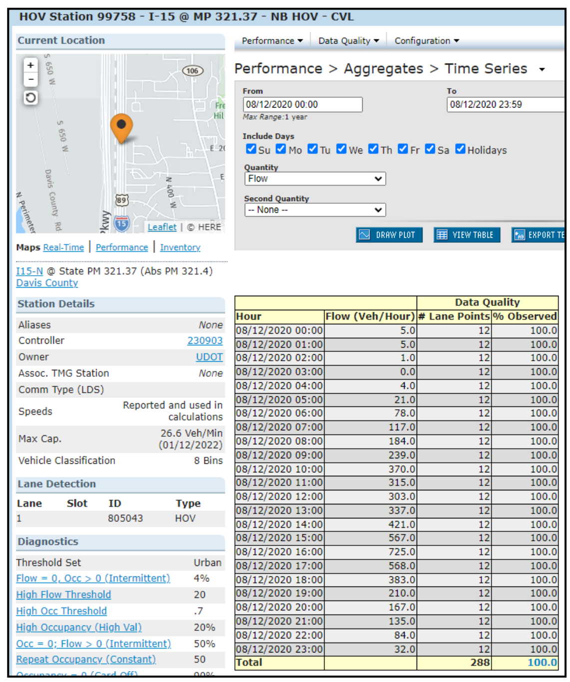
Hour	Flow (Veh/Hour)	Data Quality: # Lane Points	Data Quality: % Observed
08/12/2020 00:00	573.0	48	100.0
08/12/2020 01:00	362.0	48	100.0
08/12/2020 02:00	282.0	48	100.0
08/12/2020 03:00	254.0	48	100.0
08/12/2020 04:00	458.0	48	100.0
08/12/2020 05:00	1,148.0	48	100.0
08/12/2020 06:00	2,302.0	48	100.0
08/12/2020 07:00	3,256.0	48	100.0
08/12/2020 08:00	3,612.0	48	100.0
08/12/2020 09:00	3,725.0	48	100.0
08/12/2020 10:00	4,098.0	48	100.0
08/12/2020 11:00	4,309.0	48	100.0
08/12/2020 12:00	4,377.0	48	100.0
08/12/2020 13:00	4,657.0	48	100.0
08/12/2020 14:00	5,026.0	48	100.0
08/12/2020 15:00	5,886.0	48	100.0
08/12/2020 16:00	6,129.0	48	100.0
08/12/2020 17:00	6,240.0	48	100.0
08/12/2020 18:00	4,922.0	48	100.0
08/12/2020 19:00	3,538.0	48	100.0
08/12/2020 20:00	2,949.0	48	100.0
08/12/2020 21:00	2,374.0	48	100.0
08/12/2020 22:00	1,695.0	48	100.0
08/12/2020 23:00	1,022.0	48	100.0
Total		1,152	100.0

(b) Station 758



Hour	Flow (Veh/Hour)	Data Quality: # Lane Points	Data Quality: % Observed
08/12/2020 00:00	14.0	12	100.0
08/12/2020 01:00	12.0	12	100.0
08/12/2020 02:00	9.0	12	100.0
08/12/2020 03:00	10.0	12	100.0
08/12/2020 04:00	35.0	12	100.0
08/12/2020 05:00	269.0	12	100.0
08/12/2020 06:00	585.0	12	100.0
08/12/2020 07:00	555.0	12	100.0
08/12/2020 08:00	561.0	12	100.0
08/12/2020 09:00	450.0	12	100.0
08/12/2020 10:00	522.0	12	100.0
08/12/2020 11:00	502.0	12	100.0
08/12/2020 12:00	509.0	12	100.0
08/12/2020 13:00	481.0	12	100.0
08/12/2020 14:00	577.0	12	100.0
08/12/2020 15:00	594.0	12	100.0
08/12/2020 16:00	617.0	12	100.0
08/12/2020 17:00	686.0	12	100.0
08/12/2020 18:00	541.0	12	100.0
08/12/2020 19:00	371.0	12	100.0
08/12/2020 20:00	340.0	12	100.0
08/12/2020 21:00	309.0	12	100.0
08/12/2020 22:00	137.0	12	100.0
08/12/2020 23:00	46.0	12	100.0
Total		288	100.0

(c) Station 99755



Hour	Flow (Veh/Hour)	Data Quality: # Lane Points	Data Quality: % Observed
08/12/2020 00:00	5.0	12	100.0
08/12/2020 01:00	5.0	12	100.0
08/12/2020 02:00	1.0	12	100.0
08/12/2020 03:00	0.0	12	100.0
08/12/2020 04:00	4.0	12	100.0
08/12/2020 05:00	21.0	12	100.0
08/12/2020 06:00	78.0	12	100.0
08/12/2020 07:00	117.0	12	100.0
08/12/2020 08:00	184.0	12	100.0
08/12/2020 09:00	239.0	12	100.0
08/12/2020 10:00	370.0	12	100.0
08/12/2020 11:00	315.0	12	100.0
08/12/2020 12:00	303.0	12	100.0
08/12/2020 13:00	337.0	12	100.0
08/12/2020 14:00	421.0	12	100.0
08/12/2020 15:00	567.0	12	100.0
08/12/2020 16:00	725.0	12	100.0
08/12/2020 17:00	568.0	12	100.0
08/12/2020 18:00	383.0	12	100.0
08/12/2020 19:00	210.0	12	100.0
08/12/2020 20:00	167.0	12	100.0
08/12/2020 21:00	135.0	12	100.0
08/12/2020 22:00	84.0	12	100.0
08/12/2020 23:00	32.0	12	100.0
Total		288	100.0

(d) Station 99758

Figure B.28. Screenshots of Utah station UT_14 traffic counts for August 12, 2020 from UDOT's PeMS

Wisconsin:

Station Name: 310001
Latitude: 44.66349
Longitude: -87.744395

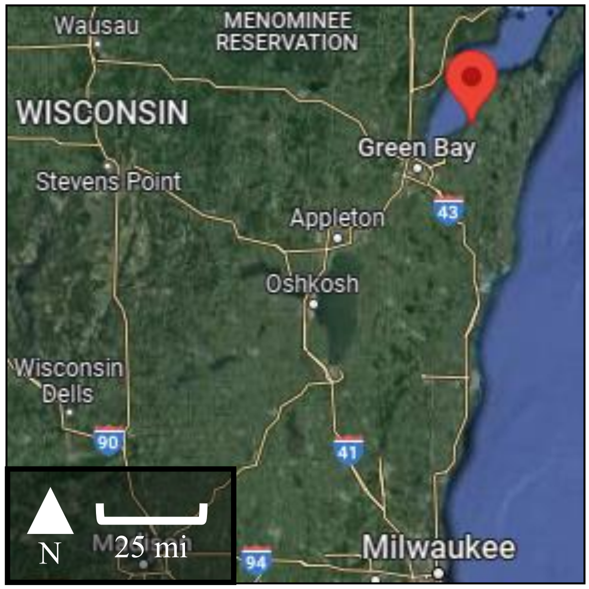


Figure B.29. Location of Wisconsin station 310001

Trajectory points: 144,772

(a) August 2020

Trajectory points: 4,483

(b) August 12, 2020

Figure B.30. Connected vehicle points for Wisconsin station 310001

Table B.15. DOT vehicle counts for a subset of August 12, 2020 for Wisconsin station 310001

Date	Day of Week	Hour	Direction	Volume by Direction	Road Volume
12-Aug-20	Wednesday	0	NB	22	48
12-Aug-20	Wednesday	0	SB	26	
12-Aug-20	Wednesday	1	NB	13	31
12-Aug-20	Wednesday	1	SB	18	
12-Aug-20	Wednesday	2	NB	10	21
12-Aug-20	Wednesday	2	SB	11	
12-Aug-20	Wednesday	3	NB	23	41
12-Aug-20	Wednesday	3	SB	18	
12-Aug-20	Wednesday	4	NB	68	136
12-Aug-20	Wednesday	4	SB	68	
12-Aug-20	Wednesday	5	NB	181	336
12-Aug-20	Wednesday	5	SB	155	

Table B.16. Hourly and resulting daily percent penetration calculations for August 12, 2020 for Wisconsin station 310001

Date	Hour	DOT Count	CV Count	Percent
8/12/2020	0	48	0	0.0%
8/12/2020	1	31	1	3.2%
8/12/2020	2	21	0	0.0%
8/12/2020	3	41	2	4.9%
8/12/2020	4	136	9	6.6%
8/12/2020	5	336	16	4.8%
8/12/2020	6	548	43	7.8%
8/12/2020	7	623	36	5.8%
8/12/2020	8	678	35	5.2%
8/12/2020	9	908	49	5.4%
8/12/2020	10	1023	73	7.1%
8/12/2020	11	1089	84	7.7%
8/12/2020	12	1023	62	6.1%
8/12/2020	13	990	65	6.6%
8/12/2020	14	1122	67	6.0%
8/12/2020	15	1272	85	6.7%
8/12/2020	16	1204	78	6.5%
8/12/2020	17	949	58	6.1%
8/12/2020	18	641	43	6.7%
8/12/2020	19	543	35	6.4%
8/12/2020	20	367	23	6.3%
8/12/2020	21	221	15	6.8%
8/12/2020	22	123	10	8.1%
8/12/2020	23	58	4	6.9%
8/12/2020	**Total**	**13995**	**893**	**6.4%**

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