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Research Support to INDOT on I-465 Southeast Variable Speed Limit and Ramp Meter Project

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16. Abstract

Traditionally, crash data, crash risk models, video recordings and user surveys have been utilized by agencies to measure the safety benefits of ramp metering technology. Connected vehicle data can now provide an agile evaluation alternative for quantifying impact of ramp meter deployments. Furthermore, in contrast to crash data, connected vehicle near miss events occur much more frequently, so the before-after evaluation can be conducted over a much shorter time period consisting of a few months, or perhaps even a few weeks.

Indiana deployed ramp meters on the southeast section of I-465 around Indianapolis, on or around May 14, 2024, which were then active primarily during the morning and evening peak hours. Additionally, Indiana deployed Variable Speed Limit (VSLs) on September 10, 2024, at 25 locations on I-465. This study was initiated to evaluate the impact of those deployments. Hard-braking events, a surrogate safety performance measure, were estimated from high-frequency connected vehicle data available at 3-second fidelity for vehicles passing through the metered ramps and the adjacent mainline interstate. A before-after analysis for the 4-5 PM peak hour showed approximately a 61% reduction in hard-braking events on mainline merge areas adjoining the metered ramps on the inner loop of I-465. Spatial analysis also showed a 70%, 41%, and 33% median reduction in mild, moderate, and severe hard-braking events per 0.1-mile segment in the entire 7.5-mile mainline corridor adjacent to metered ramps. A before-after analysis of the 10 AM–1 PM hours showed little to modest impact on speeds in 0.3-mile evaluation sections with VSL deployments.

The methodologies and performance measures provided in this paper present a framework that scales well to systematically assess and document the performance of new ramp metering and VSL deployments.

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EXECUTIVE SUMMARY

Motivation

Indiana deployed ramp meters on the southeast section of I-465 around Indianapolis, on or around May 14, 2024, which were then active primarily during the morning and evening peak hours. Additionally, Indiana deployed Variable Speed Limit (VSL) on September 10, 2024, at 25 locations on Interstate 465 (I-465). This study was initiated to evaluate the impact of those deployments.

Study

Traditionally, crash data, crash risk models, video recordings, and user surveys have been utilized by agencies to measure the safety benefits of ramp metering technology. Connected vehicle data (CV) provide the ability to monitor approximately 5% of the vehicles using Indiana roads. These data were used to assess both travel speeds and hard braking characteristics of vehicles in the study area. In contrast to crash data, CV near-miss events occur much more frequently, so the before–after evaluation can be conducted over a much shorter time period consisting of a few months or, perhaps, even a few weeks. Examples of recent hard-braking studies include: work zone operations (Desai et al., 2021), queue warning trucks (Sakhare, Desai, Mahlberg, et al., 2021), and intersection operations (Hunter et al., 2021).

This study used CV data to assess ramp meters and VSL deployments on I-465 in southeast Indianapolis. The following analyses were performed:

- Before–after evaluation of hard-braking activity at individual ramp merge areas with metered entrance ramps, using a 0.4-mi evaluation area.
- Before–after evaluation along a 7.5-mi freeway with five metered entrance ramps.
- Before–after evaluation of impact of VSL deployments on I-465 traffic speeds using 0.3-mi evaluation segments.

Results

The following results were observed from the analysis:

- A before–after analysis for the 4:00–5:00 p.m. peak hour showed approximately a 61% reduction in hard-braking events on mainline merge areas adjoining the metered ramps on the inner loop of I-465.
- Spatial analysis also showed a 70%, 41%, and 33% median reduction in mild, moderate, and severe hard-braking events, respectively, per 0.1-mi segment in the entire 7.5-mi mainline corridor adjacent to metered ramps.
- A before–after analysis of the 10:00 a.m.–1:00 p.m. hours showed little to modest impact on speeds in 0.3-mi evaluation sections with VSL deployments.

Recommendations

The study shows encouraging results on ramp meter deployments reducing hard-braking events near merge areas as well as the 7.5-mi segment of I-465. Summary graphics are developed to provide a visual tool to communicate with stakeholders the before–after impact.

The study did not find significant impact of VSL on CV speeds. Part of this may have been due to relatively limited data on deployment times. It would be desirable to enhance the reporting interval of the VSL signs.

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Indiana deployed ramp meters on the southeast section of Interstate 465 (I-465) around Indianapolis, on or around May 14, 2024, which were then active primarily during the morning and evening peak hours. Additionally, Indiana deployed Variable Speed Limit (VSLs) on September 10, 2024, at 25 locations on I-465. This study was initiated to evaluate the impact of those deployments and is structured as follows:

- Section 1: Provides an overview of the project's scope and objectives
- Section 2: Provides details on Indiana's Ramp Meter Deployment study locations and activity summaries
- Section 3: Provides details on Indiana's VSL Deployment study locations
- Section 4: Describes the connected vehicle (CV) data used in the analysis
- Section 5: Describes the methodology used to compute and process CV speeds and hard-braking events
- Section 6: Summarizes the results of the analysis in the context of both VSLs and Ramp Meters
- Section 7: Provides key findings and conclusions from this research
- Section 8: Provides an outlook on future research directions that could be adopted

1.1 Introduction

Ramp meters are a tool used to mitigate congestion and crashes on freeways. Ramp meters consist of traffic signals on freeway ramps that cycle quite frequently so that traffic is metered onto the freeway at either uniform or adaptive rates. The Federal Highway Administration (FHWA, 2020) classifies their benefits into three main categories: mobility, safety, and reduced environmental impacts. There is a mature body of literature that has documented impacts of ramp metering on reducing mainline congestion, overall delay (Ahn et al., 2007), travel times (Levinson & Zhang, 2006), and travel time reliability (Bhouri & Kauppila, 2011). The focus of this study is evaluating the safety impacts of ramp metering technology as well as assessing the impacts of VSL deployments using CV data.

1.1.1 Safety Benefits of Ramp Metering

Crash prediction models, neural network models and microscopic traffic simulations (Abdel-Aty & Wang, 2017) have been used to help quantify the safety effects of ramp metering on freeways for Interstate 95 (I-95) in Miami, Florida (Haule et al., 2021), Interstate 880 (I-880) in Hayward, California (Lee et al., 2006), and Interstate 4 (I-4) in Orlando, Florida (Abdel-Aty et al., 2009). An examination of vehicular collision data for a sample of 19 ramp meters in Northern California showed a 36% reduction in freeway collisions near on-ramp exits (Liu & Wang, 2013). Video recordings have been used to observe detailed driver behavior and acceleration profiles as users navigate a ramp meter (Wu, 2007; Yang & Tian, 2019). Traditional safety evaluations of ramp metering deployments have heavily focused on documenting driver behavior as they navigate a metered ramp with little visibility on the impacts on mainline traffic. While these techniques provide important insights into driver behavior, they require extended data collection, processing, and analysis periods, and it is very difficult to obtain high-fidelity acceleration or deceleration data. This lack of high-quality quantitative data on acceleration or deceleration rate presents an opportunity to further address this gap in the literature.

A number of studies have also utilized microscopic traffic simulation models (Allaby et al., 2007; Lee et al., 2004; Othman et al., 2022), physical sensors (Gonzales et al., 2019), detectors (Nissan & Koutsopoulosb, 2011), and other techniques to measure the impacts of VSL deployments. However, a large-scale evaluation using widely available CV data has not been conducted. This study aims to fill this research gap by leveraging CV data to conduct a before–after analysis of the impact of VSLs on traffic speeds.

1.1.2 Application of CV Data

CV data have been utilized by a number of transportation agencies to evaluate the safety benefits of multiple solutions, such as queue warning trucks (Sakhare, Desai, Mahlberg, et al., 2021), work zone safety measures (Mathew et al., 2021; Sakhare, Desai, Mathew, et al., 2021), and intersection safety (Hunter et al.,2021; Vajpayee et al., 2024), among others. Due to the availability of CV data on both the adjacent freeway and metered ramp, a more complete evaluation can be performed considering both sets of traffic profiles. Of particular interest is the ability to collect near misses by tabulating the frequency and distribution of hard-braking events.

Additionally, the availability of CV data along the entire adjacent freeway also allows for analysis of speeds at VSL deployments without having to rely on physical sensor or detector placement.

1.2 Scope and Objectives

The objective of this study is to use CV trajectory data and hard-braking events to perform a before–after evaluation of the impact of ramp metering recently deployed on Interstate I-465 in southeast Indianapolis. This includes two analysis regions:

- Individual ramp merge areas with metered entrance ramps, using a 0.4-mi evaluation area.
- Overall 7.5-mi freeway with five metered entrance ramps.

The study also utilizes CV speed data to determine change in traffic speeds before and after VSL deployment on I-465.

1.3 Dissemination of Research Results

The following research studies were prepared in part during this project to facilitate an agile dissemination of results for public and private sector stakeholders:

- Desai, J., Gartner, C., Sakhare, R. S., Cox, E. D., & Bullock, D. M. (2025). Evaluating safety benefits of ramp metering by leveraging connected vehicle data: Case study of Indiana roadways. *IEEE Open Journal of Intelligent Transportation Systems*, *7*, 190–199. https://doi.org/10.1109/OJITS.2025.3650100

A majority of the contents of this report are adapted from this research paper titled "Evaluating Safety Benefits of Ramp Metering by Leveraging Connected Vehicle Data: Case Study of Indiana Roadways" (Desai et al., 2025).

Furthermore, the findings from this study were presented to stakeholders over the course of this project at various Study Advisory Committee (SAC) meetings and engagement events, including a lectern presentation during the 2025 Purdue Road School Transportation Conference and Expo. The following sections of this technical report summarize the background and key findings of this research.

2. INDIANA RAMP METER DEPLOYMENT

2.1 Study Location

The Indiana Department of Transportation (INDOT) commenced ramp metering operations on I-465 in southeast Indianapolis between Interstate 65 (I-65) and Interstate 70 (I-70) in May 2024 (INDOT, n.d.). The period from June to July 2024 was used for tuning the ramp meter schedule and metering rates. Figure 2.1 shows a map view of the ramp metering deployments (eight solid red dots) in southeast Indianapolis on I-465 between I-65 and I-70 starting in the spring of 2024, along with an inset map of Indiana for geographical context. The analysis focuses on five metered entrance ramps in the inner loop (IL; clockwise) direction of travel of I-465, labeled in the direction of travel from "A" through "E." The ramps, in order are:

- A: Washington St., Exit 46
- B: Brookville Rd., Exit 47
- C: Shadeland Ave., Downstream of Exit 47
- D: Southeastern Ave., Exit 49
- E: Emerson Ave., Exit 52

Selected drive-through footage of a motorist's view as they approach these ramp meters at five locations is shown by the images in Figure 2.2a–e in the direction of travel. Ramp meters were active during peak hour travel periods and this study analyzed the 4:00–5:00 p.m. peak travel period for weekdays with heavy commuter traffic.

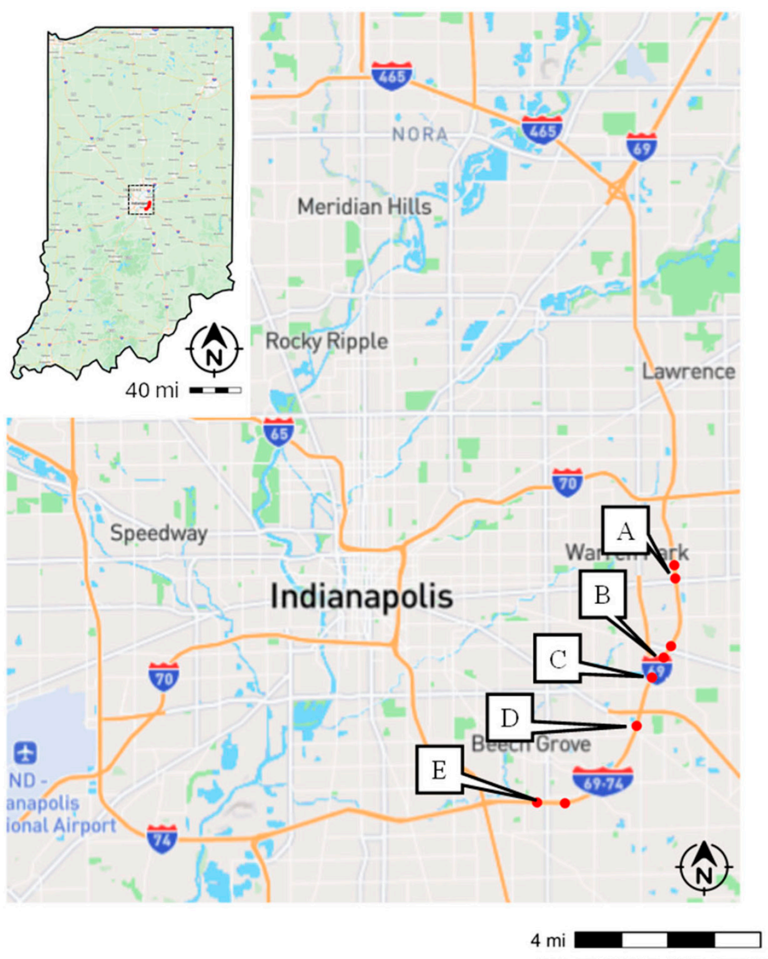
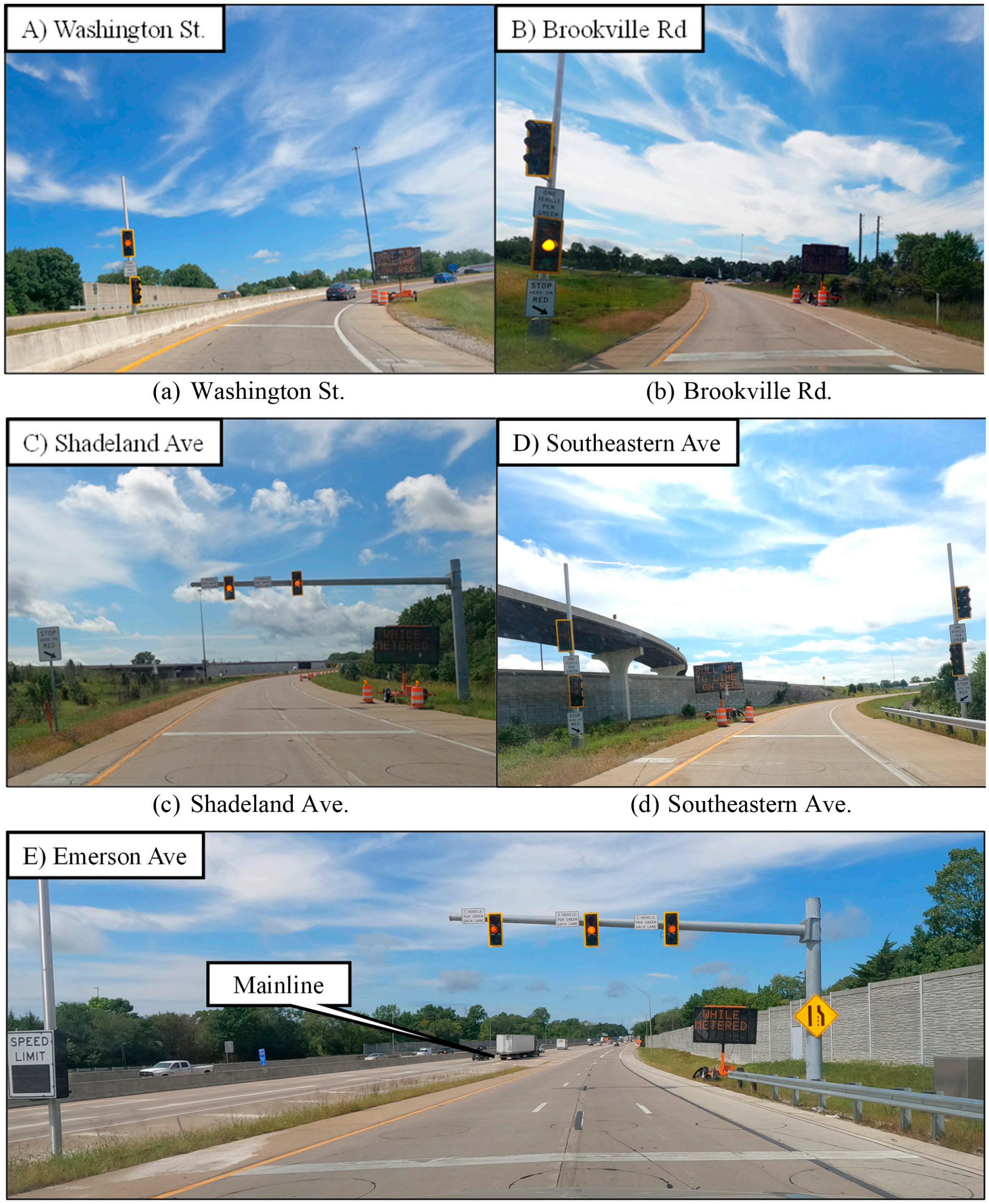


Figure 2.1 Ramp Metering Deployment Locations on I-465.



(a) Washington St.
(b) Brookville Rd.
(c) Shadeland Ave.
(d) Southeastern Ave.
(e) Emerson Ave.

Figure 2.2 Drive-Through Footage of Ramp Meters on I-465.

2.2 Activity Summary

Through activity logs provided to the research team by INDOT, times of active and inactive ramp metering were determined to select an ideal time period for a before–after analysis of the impacts of ramp metering. The metering rates ranged generally from 480–900 vehicles per lane per hour (VPLPH) and cannot exceed the 900 threshold. Values above 900 are either manual inputs (usually 1200), or rates of 1800 indicating the system initiating a queue override due to excessive queuing on the ramp—which indicates a rate of 900 for those instances. The agency also observed that the real metering rates tend to be lower than the rate indicated by the system due to driver reaction time and traffic (truck) characteristics. Figure 2.3, Figure 2.4, Figure 2.5, Figure 2.6, and Figure 2.7, show the metering rates for the five ramp meter locations analyzed on the inner loop of I-465 from August 1-25, 2024. The 4:00–5:00 p.m. period in each case shows active metering rates and was hence selected for the analysis that follows in Section 6.2.

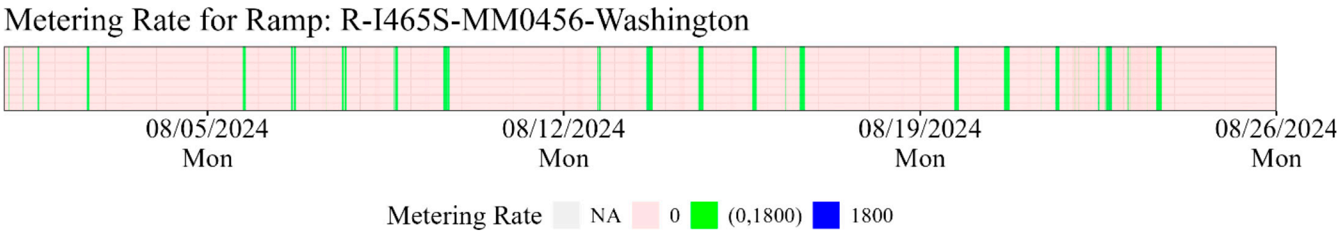


Figure 2.3 Metering Rate for Location A.

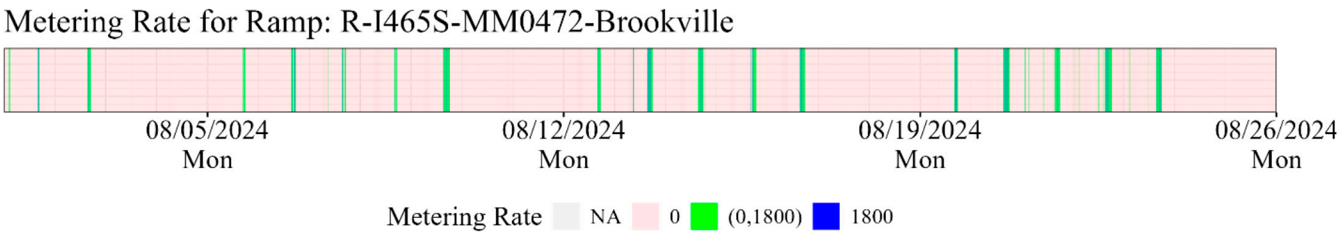


Figure 2.4 Metering Rate for Location B.

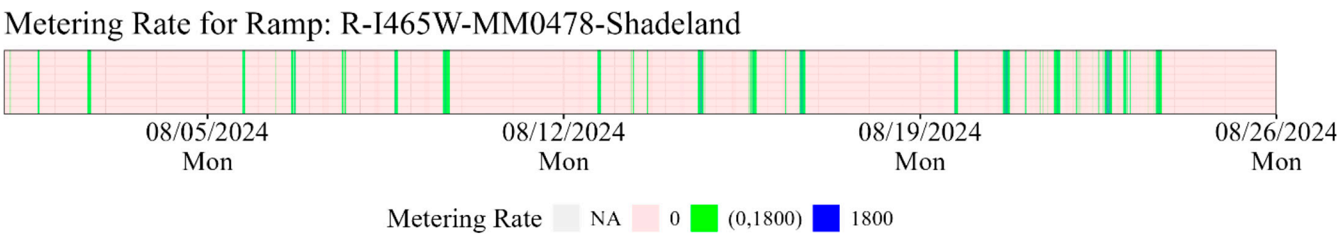


Figure 2.5 Metering Rate for Location C.

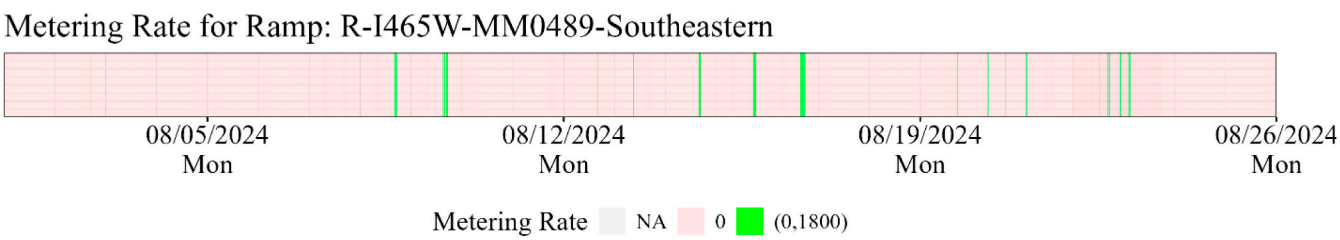


Figure 2.6 Metering Rate for Location D.

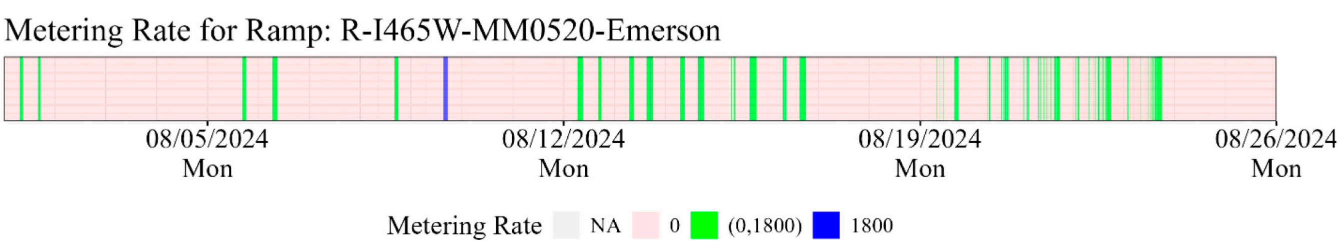


Figure 2.7 Metering Rate for Location E.

3. INDIANA VSL DEPLOYMENT

3.1 Study Location

Drive throughs of I-465 were conducted and VSL locations were recorded and have been tabulated for reference in Table 3.1. A sample image from one such drive through with a VSL visible at I-465 IL miler marker (MM) 45.8 is shown by Figure 3.1 with a speed limit of 55 mph visible. The route, mile marker location, and timestamp at which the image were collected are overlayed on the top left of the image. Activity summary logs for VSLs similar to those for ramp meters (Section 2.2) were not available and, hence, could not be used for the analysis.

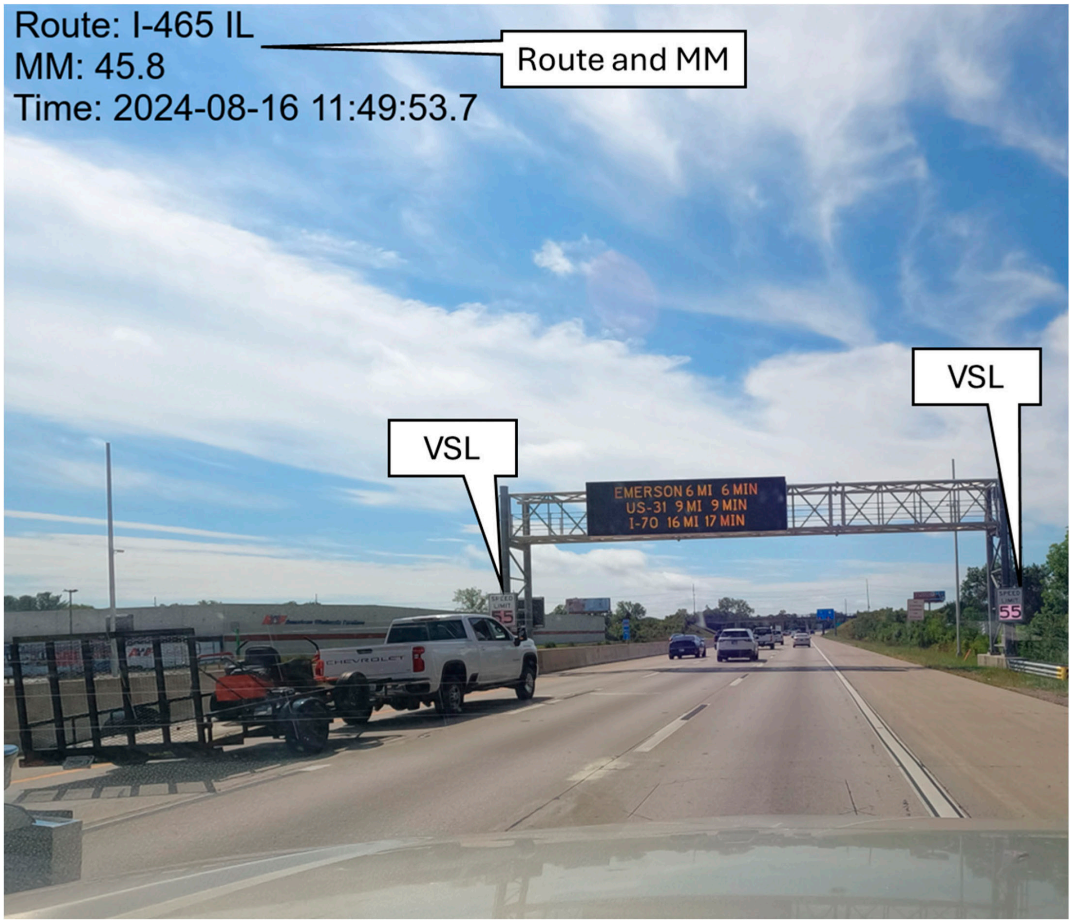


Figure 3.1 VSL at I-465 IL MM 45.8 (August 16, 2024).

TABLE 3.1
List of VSL Locations.

Route	MM	Route	MM
I-465 IL	45.1	I-465 OL	52.7
	45.8		51.4
	46.2		50.8
	46.7		50.5
	47.3		50.1
	47.8		49.5
	49.0		48.8
	49.6		48.2
	50		47.2
	50.3		46.7
	50.9		46.3
			45.6
			45.1
			44.6

4. DATA DESCRIPTION

4.1 Connected Vehicle Data

CV data available at a 3-s frequency from two third-party data providers were utilized for this study. From the period June 2023 to May 2024, no CV data were available due to a transition in companies offering CV data. Consequently, the before–after comparison was performed during the following periods:

- Before Ramp Meters were active: May 1–19, 2023 (4:00–5:00 p.m. on Weekdays)
- After Ramp Meters were active: August 5–23, 2024 (4:00–5:00 p.m. on Weekdays)

The CV data used for this study represent an approximate 4.6% market penetration on interstate roadways in Indiana (Saldivar-Carranza et al., 2024). Each CV point observation (waypoint) contains encoded geoposition; speed; heading; and a unique, anonymized trajectory identifier attribute. Using this unique trajectory identifier, deceleration under 0.2 *g* between consecutive waypoints was computed (for all waypoints a minimum of non-zero seconds apart and a maximum of 3-s apart to weed out reporting inaccuracies and outliers) and extracted. Similarly, the number of unique trajectories passing through each 0.1-mi segment of the analysis corridor were also extracted with the same waypoint frequency requirements applied. These deceleration (hard-braking) values were utilized for the analysis in the text that follows. Hard-braking events have been effectively utilized in past

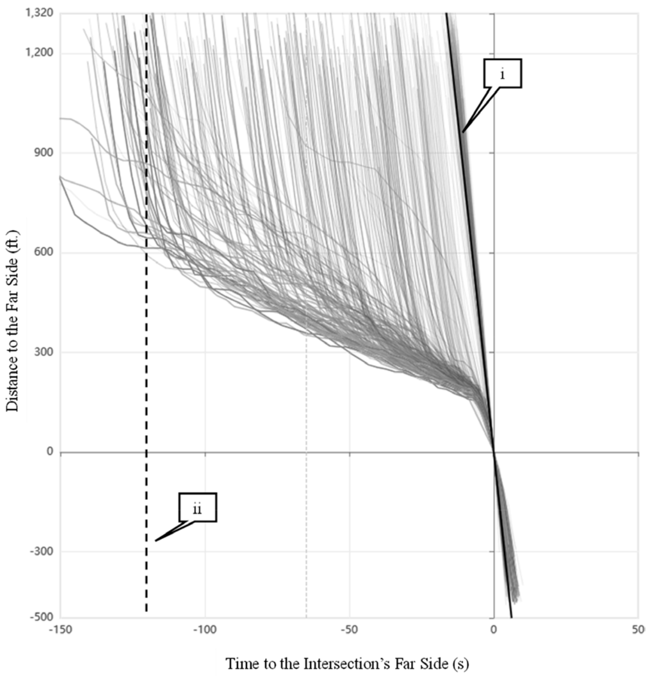


Figure 4.1 Purdue Probe Diagram of Shadeland Ave. Ramp Meter (Location C: 4:00–5:00 p.m., Weekdays August 5–23, 2024).

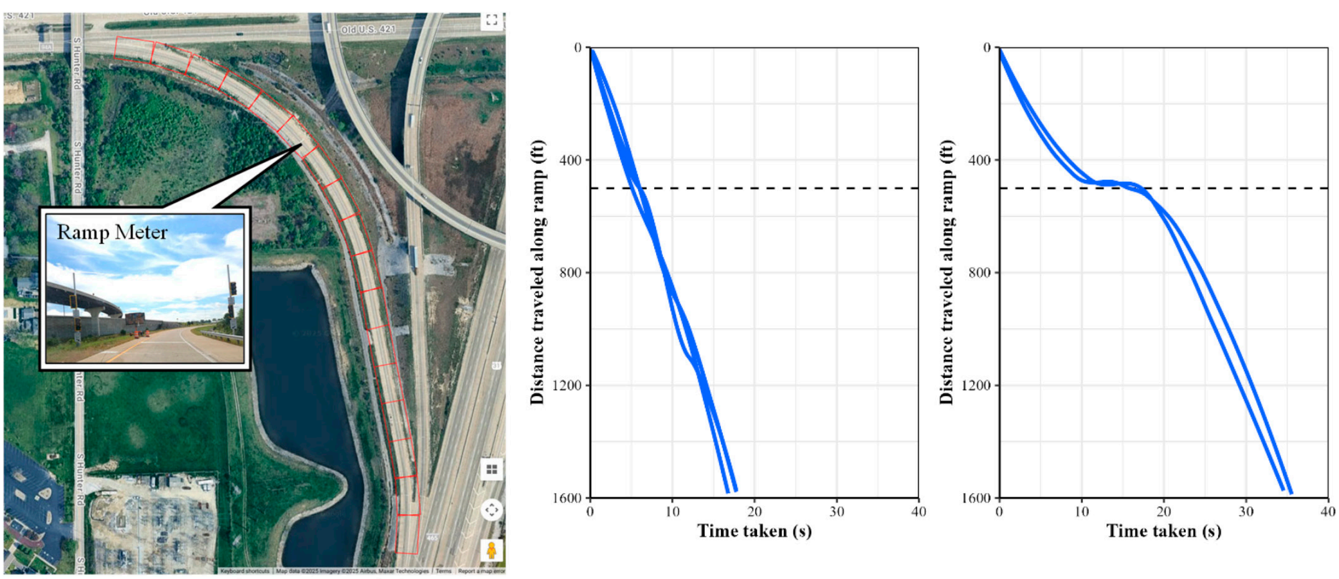
studies and have shown to be an effective surrogate safety performance measure in freeway work zones (Desai et al., 2021), at interstate entry and exit ramps (Desai et al., 2023), as well as a variety of intersection types (Hunter et al., 2021; Vajpayee et al., 2024).

4.1.1 Ramp Meter Purdue Probe Diagrams

Purdue Probe Diagrams (PPDs) are spatiotemporal plots representing the distance (y) and time (x) to a defined point on the far side of the intersection (Saldivar-Carranza et al., 2021). PPDs can similarly be used to visualize ramp metering by assuming the "far side" to be the stop bar of the meter, plus some small buffer to account for GPS error and vehicles occasionally stopping just over the stop bar. Furthermore, PPDs from any upstream intersection can be combined, drawing insights (such as spillback) upstream of the meter. Finally, downstream insights from the meter visually indicate whether trajectories can merge freely onto the interstate or must gradually merge onto the mainline while yielding to mainline traffic.

From the PPD of the Shadeland Ave. ramp meter shown in Figure 4.1, approximately 410 trajectories were observed passing through this meter; some flowed freely (Figure 4.1, Callout i) when the ramp meter was inactive, while some stopped (and thus braked) as they navigated the ramp meter queue and then the entrance ramp to I-465. In general, most vehicles passed through the ramp meter in less than 2 min (Figure 4.1, Callout ii).

Figure 4.2 illustrates two types of CV trajectories passing through one of the metered ramps on Southeastern Ave. When the ramp meter is not active (Figure 4.2b), the trajectory moves relatively unimpeded through the ramp. When the ramp meter is active, the trajectory has to stop at the meter, which is about 500 ft along the ramp (Figure 4.2c). As most trajectories during peak hours will need to stop at the ramp meter, the hard-braking characteristics are similar to those of a traffic signal and were not studied. The focus of the hard-braking



(a) Ramp Meter Location (b) Inactive Ramp Meter (c) Active Ramp Meter

Figure 4.2 Examples of Trajectories Passing Through the Southeastern Ave. Entry Ramp (Location D).

analysis was on the adjacent sections of the mainline interstate, where motorists would be merging by using the metered ramp. This allows the study of braking behavior changes by mainline motorists to allow merging traffic to enter.

5. METHODOLOGY

5.1 Processing CV Data at 0.1-Mi Resolution

For a systematic analysis, the entire evaluation mainline corridor on I-465 IL from MM 44.5 to MM 52.0 is evenly split into 0.1-mi spatial polygons covering the entire width of the roadway. Hard-braking events (point-based observations) derived from CV data are then spatially joined to these polygons, and each is assigned a corresponding MM and direction of travel. This allows for efficient analysis at the 0.1-mi resolution as well as at the entire corridor level when combined linearly. Existing studies have established the benefits of this linear referencing technique to systematically and scalably analyze billions of CV trajectory waypoints (Desai et al., 2021, 2022; Mathew et al., 2021).

6. RESULTS

The results of the analysis of CV speeds and hard-braking activity have been summarized in the text that follows in the context of VSLs and Ramp Meters.

6.1 Analysis of VSL's Impact on Speeds

The VSLs were activated from about 9:00 a.m. on September 10, 2024. CV speeds at the 11 VSL locations on I-465 IL and 14 locations on I-465 outer loop (OL) were compared for a before period (August 12–16) with an after period when VSLs were active (October 14–18) for 2024. Cumulative frequency distributions of these speeds for each VSL location (0.3-mi section VSL location as well as 0.1 mi upstream and downstream of VSL) are documented in Figure 6.1 and Figure 6.2. Very little to modest impact on speeds are observed at the VSL locations for the after period compared to before any VSLs were active. As deployment logs from VSLs were not available, a common time period of 10:00 a.m.–1:00 p.m. was chosen for this analysis for consistency, as it was clear of any incidents in both the before and after periods. The standard roadway speed limit of 55 mph is indicated by a red dashed vertical line on each frequency distribution plot.

6.2 Analysis of Ramp Meter's Impact on Mainline Hard-Braking

The following text discusses the analysis to quantify the change in hard-braking behavior at merge areas of metered ramps, and the overall corridor containing five metered ramps. For a consistent comparison, three weeks of data from 4:00–5:00 p.m. on weekdays between May 1–19, 2023, were utilized as a "before" dataset. This was compared with three weeks of data from 4:00–5:00 p.m. on weekdays between August 5–23, 2024, as an "after" dataset corresponding to a period where ramp metering deployments had been active for more than three months starting May 2024. Additionally, the severity of hard-braking events has been categorized into three distinct bins:

- mild (0.2–0.25 *g*)
- moderate (0.25–0.3 *g*)
- severe (> 0.3 *g*).

This presents a novel approach at being able to customize hard-braking thresholds per an agency's requirement rather than relying on original equipment manufacturer (OEM) determined thresholds of instantaneous hard-braking events.

6.2.1 Impact on Merge Areas

The merge point (a 0.1-mi segment) of each metered ramp with the mainline interstate is identified, and a 0.1-mi upstream segment and two 0.1-mi downstream segments are identified for analysis of hard-braking activity impacts near merge areas of metered ramps. A spatial representation of hard-braking activity near the Brookville Rd. ramp (Location B) is visualized by Figure 6.3. In the before period, a cluster of hard-braking events is visible exactly at the merge point (Figure 6.3a, Callout "Merge") and downstream of the merge point. However, this cluster is significantly sparser in the after period, suggesting discernible safety benefits of ramp metering resulting in mainline motorists having to hard-brake less due to the regulated flow of merging traffic coming from the ramp meter instead of tightly packed platoons. A single CV trajectory may experience consecutive instances of hard-braking, and all such events have been considered for this part of the analysis.

Table 6.1 documents the change in hard-braking event counts before and after ramp metering deployment on five ramps. The merge areas are defined as a 0.4-mi-long spatial polygons, extending 0.1 mi upstream of the merge point and 0.2 mi downstream. Across all five merge areas, a 61% reduction in hard-braking events was observed. The largest reductions were observed in the moderate hard-braking events category, followed by the severe and mild events. All categories of hard braking experienced a reduction in the after period, except for the Severe category for Ramp A, which may be attributable to a small sample size or a freeway incident.

6.2.2 Impact on Mainline Corridor

In contrast to the prior section, and to avoid duplication of events, if a CV trajectory experienced multiple hard-braking events over consecutive waypoints, only the first hard-braking event was considered for this part of the analysis. A total of 4,230 estimated hard-braking events across the 7.5-mi analysis corridor before and after ramp metering deployments have been graphically represented in Figure 6.4a. The approximate MM locations where each metered ramp merges with the mainline interstate have been shown by dotted lines and labels A to E. Hard-braking event counts at each MM in the before period from May 2023 are shown in translucent bars, while those from the after period in August 2024 are shown by opaque bars to the right of the translucent bars.

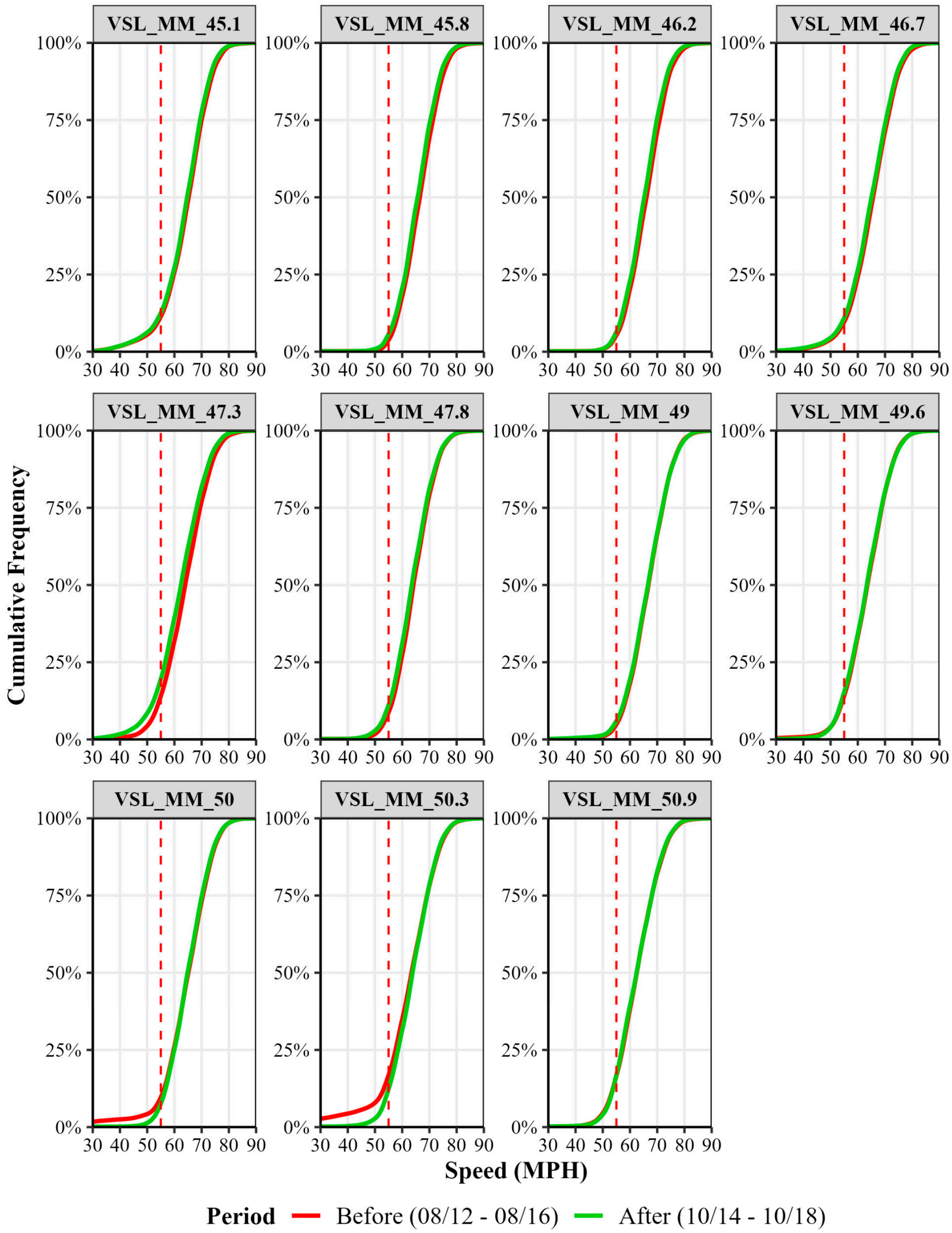


Figure 6.1 Impact of VSL on Speeds on I-465 IL.

A reduction in hard-braking was observed throughout the corridor at almost every 0.1-mi segment bin. Due to the time gap between the before and after evaluation periods, a normalized hard-braking count (dividing hard-braking event counts by the number of unique trajectories passing through that MM) is also summarized in Figure 6.4b. The normalized version also shows very consistent results and systematic reductions from the before to after period across the analysis corridor. This suggests a systematic reduction in hard-braking events after the ramp metering deployment.

A smoothed cumulative frequency distribution plot of the raw hard-braking event counts, as well as normalized hard-braking event counts, separated by severity category for every 0.1-mi segment along the analysis corridor (75 segments totaling 7.5 mi), is shown in Figure 6.5. The distributions clearly show a leftward shift in the after period compared to

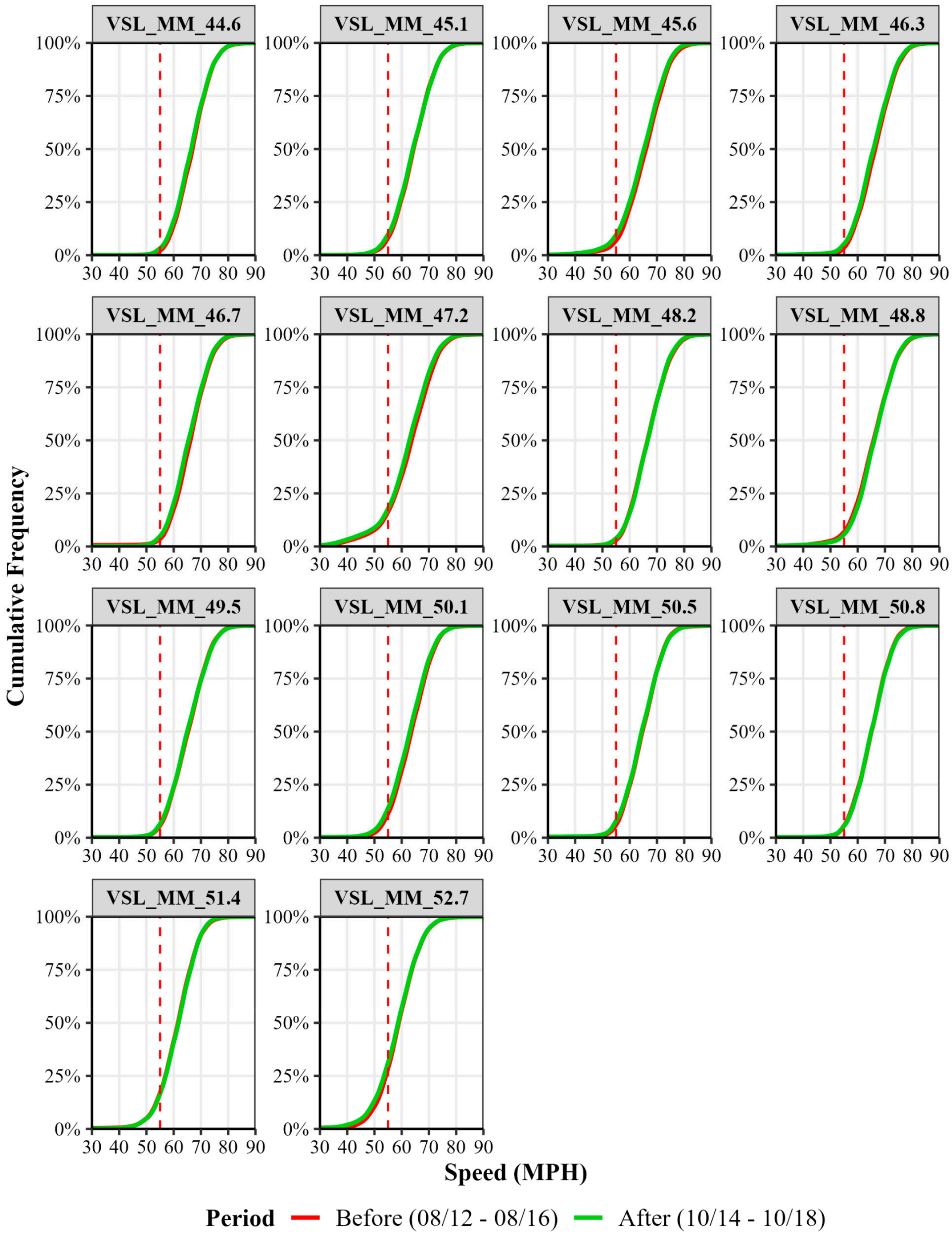
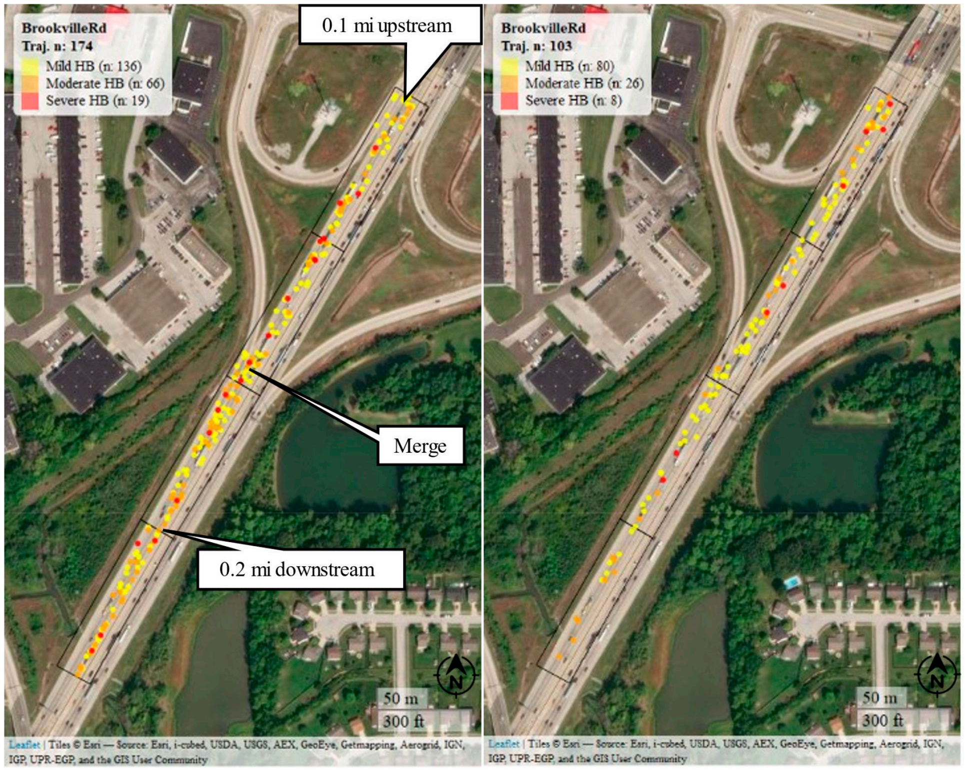


Figure 6.2 Impact of VSL on Speeds on I-465 OL.

before, pointing to a reduction in the number of raw, as well as normalized hard-braking, events per 0.1-mi segment of the analysis corridor.

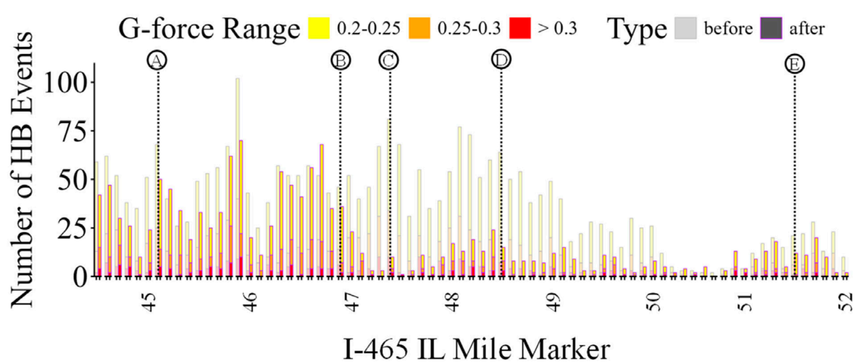
Exact reductions in hard-braking events are tabulated for the overall 7.5-mi I-465-IL corridor in Table 6.2, categorized by the three severity types. Hard-braking event counts at the mild, moderate, and severe levels on average for every 0.1-mi segment dropped by 48%, 47%, and 33%, respectively, after ramp metering. Normalized event counts dropped by 49%, 48%, and 33% on average, respectively.

The observed reductions in hard braking suggest aggressive or evasive braking behavior being reduced by half across the corridor for the mild and moderate levels and by about a third for the severe level. This provides encouraging insights into the impacts of ramp metering not only in adjacent merge areas, but also on the overall adjacent mainline corridor.

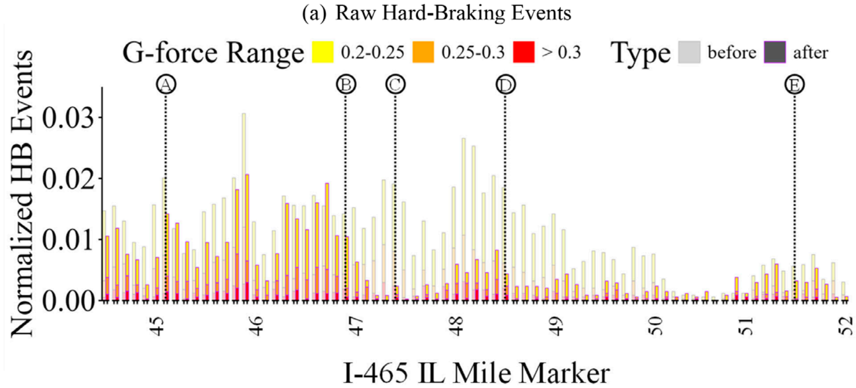


(a) Before (May 2023) (b) After (August 2024)

Figure 6.3 Mainline Hard-Braking Events Before and After Ramp Metering at Brookville Rd. Ramp (Location B).

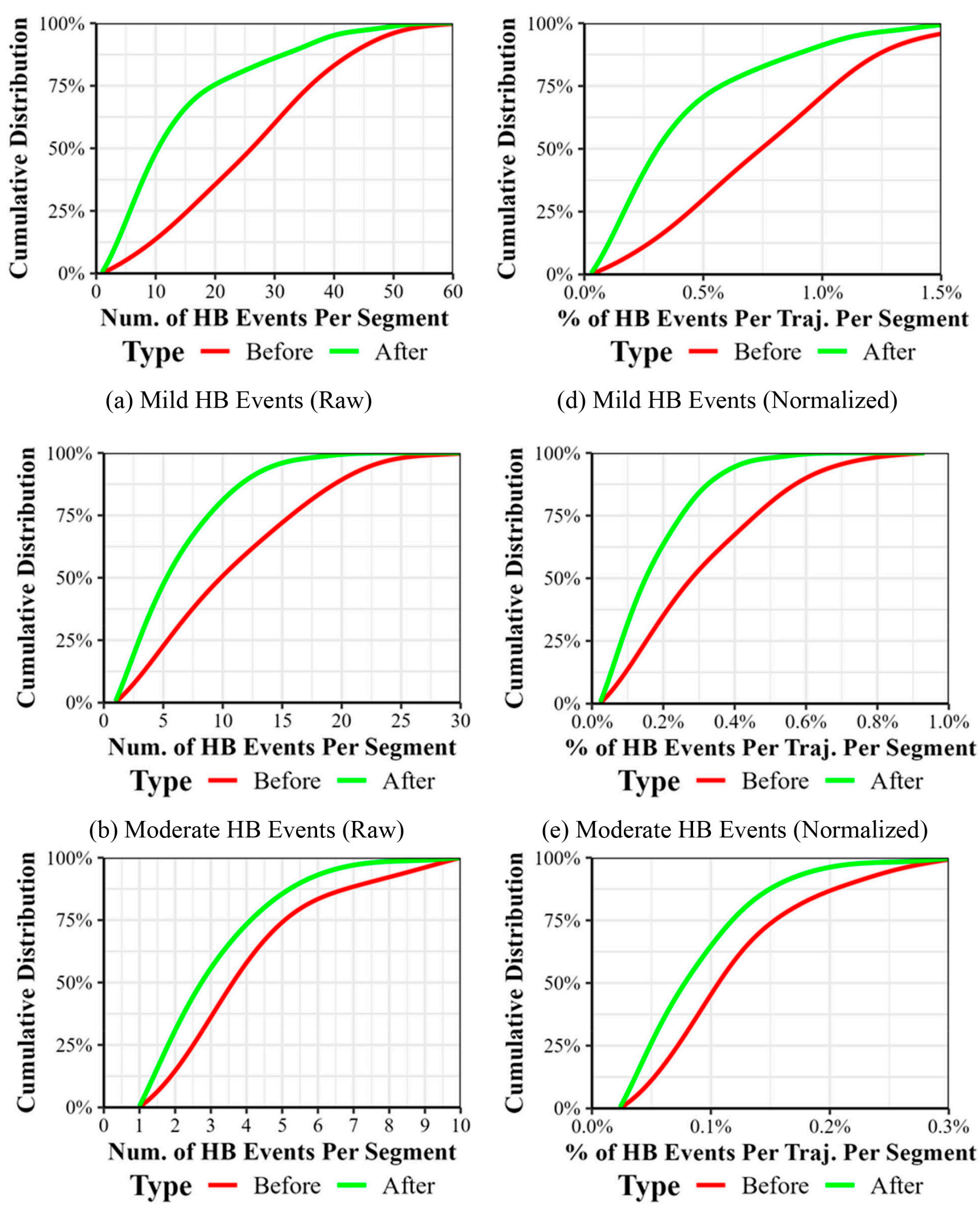


(a) Raw Hard-Braking Events



(b) Normalized Hard-Braking Events by Trajectory Count

Figure 6.4 Raw and Normalized Hard-Braking Events by MM Before and After Along the Analysis Corridor.



(a) Mild HB Events (Raw)
(d) Mild HB Events (Normalized)
(b) Moderate HB Events (Raw)
(e) Moderate HB Events (Normalized)
(c) Severe HB Events (Raw)
(f) Severe HB Events (Normalized)

Figure 6.5 Raw and Normalized Hard-Braking (HB) Events Per 0.1-mi Segment Before and After Cumulative Frequency Distributions.

TABLE 6.1
Hard-Braking Events Near Merge Areas.

Location	Before (May 2023)			After (Aug 2024)			% Change		
	Mild	Moderate	Severe	Mild	Moderate	Severe	Mild	Moderate	Severe
A	131	58	10	120	31	14	-8%	-47%	40%
B	136	66	19	80	26	8	-41%	-61%	-58%
C	172	82	28	11	4	3	-94%	-95%	-89%
D	171	64	28	40	16	9	-77%	-75%	-68%
E	67	24	11	38	12	3	-43%	-50%	-73%
Total	677	294	96	289	89	37	-57%	-70%	-61%
Overall		1,067			415			-61%	

TABLE 6.2
Summary Statistics of Change in Hard-Braking Activity on I-465 IL for Three Severity Levels.

Hard-Braking Severity	Statistic	Raw Events (HB Count) Before	Raw Events (HB Count) After	Raw Events (HB Count) % Change	Normalized Events (HB Count/Trajectory Count) % Before	Normalized Events (HB Count/Trajectory Count) % After	Normalized Events (HB Count/Trajectory Count) % % Change
Mild	25th Percentile	15.0	4.0	-73%	0.43%	0.12%	-73%
	50th Percentile	27.0	8.0	-70%	0.70%	0.23%	-67%
	75th Percentile	34.0	16.3	-52%	1.02%	0.48%	-52%
	Mean	25.2	13.0	-48%	0.73%	0.37%	-49%
Moderate	25th Percentile	4.0	2.0	-50%	0.12%	0.06%	-54%
	50th Percentile	8.5	5.0	-41%	0.24%	0.13%	-47%
	75th Percentile	15.0	8.0	-47%	0.45%	0.24%	-47%
	Mean	10.1	5.3	-47%	0.29%	0.15%	-48%
Severe	25th Percentile	2.0	1.0	-50%	0.06%	0.03%	-54%
	50th Percentile	3.0	2.0	-33%	0.10%	0.06%	-43%
	75th Percentile	5.0	4.0	-20%	0.15%	0.11%	-27%
	Mean	4.0	2.7	-33%	0.12%	0.08%	-33%

7. CONCLUSION

This study presented a before-after analysis of hard-braking events observed on the mainline interstate in the vicinity of ramp meter deployments in southeast Indianapolis. Analyses were conducted for the 4:00–5:00 p.m. peak commuter hour on weekdays over three weeks in August 2024, compared to three weeks in May 2023, prior to any deployment. Widely available CV data at representative market penetration rates were utilized for the analysis, and hard-braking events were estimated using pairwise velocity differences between consecutive CV trajectory waypoints. Hard-braking events were categorized as mild (0.2–0.25 *g*), moderate (0.25–0.3 *g*), or severe (> 0.3 *g*) and tabulated for 5 ramps (Table 6.1), and the overall 7.5-mi freeway segment (Table 6.2). The analysis included both a raw hard-braking event count comparison and one normalized by the trajectory count for each period.

- Hard-braking counts in the freeway segments adjacent to the ramp meters (0.1 mi upstream of the merge point to 0.2 mi downstream of the merge point) were analyzed at five locations. On average, mild, moderate, and severe hard-braking counts were reduced by 57%, 70%, and 61%, respectively (Table 6.1).
- The total hard-braking counts along the 7.5-mi corridor were analyzed in 0.1-mi segments for three severity levels (Table 6.2). Across the 75 segments, the median reduction per segment in hard braking for mild, moderate, and severe was 70%, 41%, and 33%, respectively.
- If the hard-braking counts are normalized by the number of trajectories, the median reduction per segment in normalized hard-braking counts for three severity levels of mild, moderate, and severe was 67%, 47%, and 43%, respectively (Table 6.2).

Additionally, the study found little to modest impact on freeway speeds in 0.3-mi sections with VSL deployments (Table 3.1) for the analysis hours of 10:00 a.m.–1:00 p.m. (Figure 6.1 and Figure 6.2).

8. FUTURE RESEARCH

This study's findings suggest a significant safety performance benefit of ramp metering. Furthermore, these techniques can be scaled for any deployment by simply procuring the appropriate connected vehicle data during the before and after periods. Finally, three different severity levels for hard braking were used in this study. Although there were dramatic changes at each of the severity levels, the literature is still evolving regarding the most appropriate threshold to use for these types of studies. Lower thresholds provide larger sample sizes and can be used to identify modest disturbances, while higher thresholds are indicative of more aggressive behavior and may correlate better with crash data and/or driver perception of risk.

Finally, the study showed little to modest impact on speeds from VSL deployments. If deployment logs with posted variable speed limits were to be made available, further granular analysis may be conducted during specific timeframes of VSL deployment to better isolate and understand the impacts to traffic speeds.

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APPENDICES

Appendix A. List of Acronyms

CV	Connected Vehicle
DOT	Department of Transportation
FHWA	Federal Highway Administration
PPD	Purdue Probe Diagram
INDOT	Indiana Department of Transportation
MM	Mile Marker
VSL	Variable Speed Limit
IL	Inner Loop
HB	Hard-braking
OEM	Original Equipment Manufacturer
OL	Outer Loop
VPLPH	Vehicles Per Lane Per Hour

About the Joint Transportation Research Program (JTRP)

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

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

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

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