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Evaluation of Ramp Metering Effectiveness Along the I-35 Corridor in the Kansas City Metropolitan Area

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16 Abstract

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PREFACE

The Kansas Department of Transportation's (KDOT) Kansas Transportation Research and New-Developments (K-TRAN) Research Program funded this research project. It is an ongoing, cooperative, and comprehensive research program addressing transportation needs of the state of Kansas utilizing academic and research resources from KDOT, Kansas State University and the University of Kansas. Transportation professionals in KDOT and the universities jointly develop the projects included in the research program.

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Abstract

This research investigated the safety and operational benefits of ramp metering along the I-35 corridor in the Kansas City metropolitan area. A before-and-after study was conducted to compare selected performance measures, with a "before" period from August 2015 to December 2015 and an "after" period from October 2021 to February 2022. The research evaluation focused on six locations during morning and afternoon peak periods. Analysis of crash frequency revealed a significant crash reduction range of 54.8%–83.3%, except at the I-35 N @ 7th St. Trfy. location, where the number of crashes remained unchanged. Crash rates also decreased 13%–82.5% at most locations, except for the I-35 N @ 7th St. Trfy. location, where the crash rate increased by 5.8% due to reduced traffic volumes. In addition, most locations had increased speeds, and locations that previously experienced recurring congestion became uncongested during peak hours. Most notable average speed gains without significant flow rate changes were observed at the I-35 S @ 7th St. location (20% during afternoon peak), the I-35 S @ Southwest Blvd. location (39.5% during morning peak and 72.8% during afternoon peak), and the I-35 N @ Johnson Dr. location (30.6% during morning peak). Because the results demonstrated their vast safety and operational benefits, this study recommends continued deployment of ramp meters along the I-35 corridor. However, the ramp meters at I-35 N @ 7th St. Trfy. should be further investigated since no safety or operational benefits were identified.

Acknowledgments

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Chapter 1: Introduction

1.1 Background

Increasing traffic congestion motivates transportation operators to identify innovative methods to efficiently utilize available freeway capacity while improving driver safety and mobility. These methods include the implementation of advanced technologies and procedures in freeway and ramp management programs. Many transportation agencies throughout the United States use ramp management strategies to control freeway access and increase operational benefits. These strategies control access to specific ramps, either periodically or permanently, or control the rate vehicles enter a freeway. Combinations of ramp management strategies, such as ramp closures, ramp metering, special-use treatments, and ramp treatments, are typically used (Jacobson et al., 2006).

Ramp metering, one of the most efficient ramp management strategies, utilizes on-ramps with traffic signals to temporarily limit the amount of freeway-entering traffic. The traffic signal provides very short green signals that allow a maximum of two vehicles to enter at each cycle. Multiple algorithms and approaches define meter operations and determine the vehicle release rate, including pre-timed and traffic-responsive algorithms. The rates in pre-timed operation are preset based on historical traffic conditions and follow a time-of-day schedule. Although pre-timed operation is the simplest, least expensive solution, it cannot adjust for unpredicted situations, such as non-recurrent congestion. Comparatively, real-time field data are used to calculate the ramp metering rates in traffic-responsive control.

Ramp metering, which has been used successfully since the late 1950s throughout the United States and internationally, can reduce traffic congestion, resulting in more efficient use of existing capacity. Ramp metering is commonly associated with increased throughput, higher speeds, decreased travel times, and reduced fuel consumption and vehicle emissions. In addition, results from field implementations in the United States have shown 9%–173% speed increases, smoother traffic flow entering the freeway, and improved driver safety due to reduced stop-and-go traffic, including a 15%–50% reduction in collision rate, especially rear-end and sideswipe collisions (Jacobson et al., 2006). Potential negative impacts of ramp metering include traffic diversions to alternative routes to avoid metered ramps and inequity since ramp metering typically favors motorists that make long trips versus short trips within the metered area.

Ramp metering was first implemented in the Kansas City metropolitan area in 2008 on seven interchanges along a 5-mile stretch of Interstate 435 (I-435) between Metcalf Avenue in Kansas and the 3-Trails Memorial Crossing Highway in Missouri. The Corridor Adaptive Ramp Metering Algorithm (CARMA), a system-wide traffic responsive, was implemented along this corridor. CARMA is an alteration of the System Wide Adaptive Ramp Metering (SWARM) algorithm currently utilized in California (Paesani et al., 1997). Results of metering evaluations 6 months and 12 months after the installation showed a 64% decrease in vehicle crashes during a.m. and p.m. peak periods, while travel times at most sections decreased or remained the same and demand increased by 20% (KC Scout, 2011).

In 2016–2017, KC Scout, Kansas City's bi-state traffic management system, implemented ramp metering along five junctions on a corridor of Interstate 35 (I-35) between the Kansas/Missouri state line and 67th Street. The ramp meters initially utilized the CARMA algorithm, similar to the I-435 corridor, but KC Scout implemented a new algorithm, Transuite, in 2018. In addition, construction work along I-35 at 75th Street altered traffic patterns and delayed deployment of the ramp meters. After considerable testing and evaluation in 2019, the new ramp meter controllers finally operated as intended in early 2020. However, the emerging COVID-19 pandemic at that time significantly impacted traffic worldwide, resulting in insufficient traffic demands for ramp metering on I-35. After several months, traffic gradually increased, and the meters were turned on in August 2021.

1.2 Objectives

The primary objective of this project was to investigate the safety and operational benefits of ramp meters along I-35 using a before-and-after evaluation. The "before" period was July to December 2015, while the "after" period was October 2021 to February 2022 due to significant delays in ramp metering construction, testing and deployment of the most recent algorithm, and impacts of the COVID-19 pandemic. The evaluation included safety and operational performance measures, such as number and types of crashes in the vicinity of the junctions studied, as well as speed, demand, and travel time changes. Research results highlight the benefits of ramp meters for the general public and transportation officials.

Chapter 2: Review of Current Practice

Ramp metering utilizes traffic signals on ramps to regulate traffic entering the mainline from the on-ramp to prevent the formation of congestion (Jacobson et al., 2006). If implemented correctly, ramp metering also has been shown to enhance roadway performance. Many ramp metering algorithms, from localized (single on-ramp) to system-wide or coordinated (multiple on-ramps), have been deployed and tested (Jacobson et al., 2006). This chapter reviews common ramp metering strategies and their impacts on transportation safety and operations.

2.1 Local Ramp Metering Strategies

Local ramp metering strategies regulate a single on-ramp as an independent system. Early traffic-responsive algorithms were based on feedforward philosophy, such as demand capacity (DC) and Percent-Occupancy (OCC) algorithms, as well as Asservissement Linéaire d'Entrée Autoroutière (ALINEA), a popular feedback philosophy (Papamichail et al., 2010). The primary difference between feedforward (open-loop) and feedback (closed-loop) is that the system output is not used in the next iteration in feedforward systems. The detectors in feedback systems are usually installed downstream of the on-ramp where the merge occurs (Papamichail et al., 2010).

2.1.1 Demand Capacity

The Demand Capacity (DC) ramp metering strategy is a feedforward disturbance compensation strategy that uses flow upstream of the ramp (Masher et al., 1975; Koble & Samant, 1980). This algorithm, field-tested in Boulevard Périphérique in Paris, predefines maximum and minimum ramp metering rates (Papageorgiou et al., 1997). Because ramp flow is the difference between the downstream capacity and the upstream flow, the ramp flow increases (or decreases) with the decrease (or increase) of the upstream flow. The DC algorithm also uses occupancy to determine freeway congestion and subsequently minimizes the ramp rate if congestion is determined.

2.1.2 Percent-Occupancy

The Percent-Occupancy (OCC) ramp metering strategy is a feedforward disturbance compensation strategy that uses upstream ramp occupancy (Koble & Samant, 1980). Similar to the DC strategy, OCC defines a maximum and a minimum rate and assumes a linear relationship between flow and occupancy. However, the OCC is less accurate than the DC strategy (Smaragdis & Papageorgiou, 2003).

2.1.3 Asservissement Linéaire d'Entrée Autoroutière

The ALINEA ramp metering strategy is a feedback-controlled strategy that uses occupancy downstream of the ramp (Papageorgiou et al., 1991). This strategy utilizes the outputs of its previous iteration metering rate $r(k-1)$ and downstream occupancy $o_{out}(k-1)$ for the current iteration. ALINEA uses Equation 2.1 to calculate the ramp metering rate.

$$\boldsymbol{r(k) = r(k-1) + K_R}[\hat{o} - \boldsymbol{o_{out}(k)}]$$

Equation 2.1

Where:

$r(k)$ = the current ramp metering rate in seconds,

$r(k-1)$ = the previous iteration ramp metering rate in seconds,

K_R = a regulator parameter (smoothing factor),

$\hat{o}$ = the desired downstream occupancy, and

o_{out} = the measured occupancy in vehicles per mile.

ALINEA is a popular, robust local algorithm with many extensions, including FL-ALINEA, UP-ALINEA, UF-ALINEA, AD-ALINEA, X-ALINEA/Q, and PI-ALINEA (Shaaban et al., 2016). Each extension has its own unique algorithm and is derived either for certain circumstances in the system or as a new method to control ramp metering.

2.2 Coordinated Ramp Metering Strategies

Coordinated ramp metering is commonly used to manage freeway facilities with traffic congestion, and coordinated ramp metering algorithms coordinate multiple metered ramps to prevent or minimize congestion. These algorithms assign rates to each metered ramp while considering the benefits of the entire facility, not only local segments. The following sections describe field-tested coordinated strategies.

2.2.1 METALINE

METALINE is the integral coordinated system version of ALINEA (Papageorgiou et al., 1990). METALINE was implemented in Boulevard Périphérique in Paris, France, as an incident controlling algorithm. Evaluation results of METALINE and ALINEA via simulation revealed that METALINE more rapidly dissolves congestion in the case of unexpected incidents, but both systems demonstrated approximately the same performance under normal conditions (recurrent congestion).

2.2.2 Zone Algorithm

The Zone algorithm balances entering and exiting flows in a predefined freeway section, or metering zone (Stephanedes, 1994; Zhang et al., 2001). This algorithm divides the freeway into metering zones measuring 3–6 miles long, and each metering zone may have metered and non-metered ramps and off-ramps.

2.2.3 Fuzzy Logic Control

Fuzzy logic, originally developed to produce home appliances, has also been used in automobiles and the construction industry (Zadeh, 1965). Fuzzy logic control (FLC) is a simple algorithm based on adjusting weighted controlling traffic parameters to optimize system operation (Taylor et al., 1998). FLC has been field tested on the A12 freeway between the Hague and Utrecht in the Netherlands and demonstrated an increase in travel speed and bottleneck capacity by 35% and 5%–6%, respectively. A benefit of FLC is that it is less sensitive to imprecise or missing inputs because it uses qualitative inputs instead of quantitative inputs from a process called "fuzzification."

2.2.4 HEuristic Ramp-metering CoOrdination

HEuristic Ramp-metering CoOrdination (HERO) is a linked algorithm that uses master-slave structure to manage on-ramp metering rates (Papamichail & Papageorgiou, 2008). HERO assigns the master role to the downstream on-ramp where the bottleneck occurs because ALINEA implements queue control with insufficient ramp storage. HERO assigns upstream on-ramps as slaves and uses their ramp storage for the master ramp. HERO coordinates and controls the upstream on-ramp (slave) metering rate by assigning minimum queue length.

2.2.5 System Wide Adaptive Ramp Metering

The System Wide Adaptive Ramp Metering (SWARM) algorithm is comprised of two independent algorithms in which the more restrictive is used to control the ramp metering rate. The first algorithm, SWARM1, which is based on forecasting and system-wide apportioning, uses traffic density to maintain the roadway under the saturation density level (Paesani et al., 1997; Bogenberger & May, 1999). SWARM1 forecasts density trends from previous interval data using linear regression and Kalman filtering and then computes excess density in the freeway to calculate the volume reduction value or volume excess, which are then distributed to the upstream ramp meters as metering rates using weight factors based on ramp demands and queue storage. The second algorithm, SWARM2, is a local traffic responsive system that converts measured densities into metering rates using linear conversion. However, SWARM2 relies on the accuracy of the density predictions in SWARM1 to operate effectively.

2.3 Ramp Metering Evaluations

Several studies have evaluated ramp metering algorithms using field data or simulation data to assess safety and operational impacts of ramp metering strategies along freeways. For example, Papamichail et al. (2010) evaluated the HERO algorithm along six consecutive ramps on a Monash freeway in Australia. The previous ramp metering strategy (not specified) was used as the baseline for comparison. The implementation of HERO resulted in a 4.7% increase in the morning average flow rate and a 35% increase in the average speed as well as an 8.4% increase in flow rate during the afternoon peak and a 58.6% increase in speed. The results also showed improvements in travel time reliability and mean speed deviation. A similar evaluation of the HERO algorithm along the M1 and M3 freeways in Australia by Faulkner et al. (2014) showed that morning peak travel speed increased by 7%, throughput increased by 4%, and travel time reliability increased from 19% to 56%, excluding traffic incidents compared to a fixed-time strategy.

The ALINEA algorithm was field tested along the A6W motorway in Paris, France, between September 2005 and January 2007 (Bhouri & Haj-Salem, 2009). Compared to no control, ALINEA reduced the total travel time by 9.8% and increased the mean speed by 4.3%. In addition, ALINEA improved the motorway by 31% for its misery index (MI), 37% for the buffer index (BI), and 28% for the planning time index (PTI).

Taylor and Meldrum (2000) compared the FLC algorithm to a local algorithm and the bottleneck algorithm along Interstate 90 (I-90) and Interstate 405 (I-405), respectively, in Seattle, Washington. On I-90, the FLC decreased occupancy by 8.2% and increased throughput by 4.9% compared to the local algorithm. However, longer ramp queues were observed for the FLC. On I-405, the FLC resulted in slightly increased occupancy and throughput compared to the bottleneck algorithm, but ramp queues were much longer for the bottleneck algorithm.

Taale et al. (1996) evaluated the ALINEA, FLC, and the Rijkswaterstaat (RWS) algorithms on the A12 motorway from the Hague to Utrecht in the Netherlands. Evaluation results showed that the ALINEA had 4,000 veh/hr, the RWS had 4,048 veh/hr, and the FLC had 4,256 veh/hr, while travel times were 6.2 minutes for the ALINEA, 6.0 minutes for the RWS, and 3.9 minutes for the FLC.

Chapter 3: Data Collection

3.1 Study Location

Figure 3.1 shows the locations of the ramp meters along the I-35 corridor in this study. As shown, four ramp meters were in the southbound direction (67th St., 18th St. Expy., Southwest Blvd., and 7th St. Trfy.), and two meters were in the northbound direction (Johnson Dr. and 7th St. Trfy.).

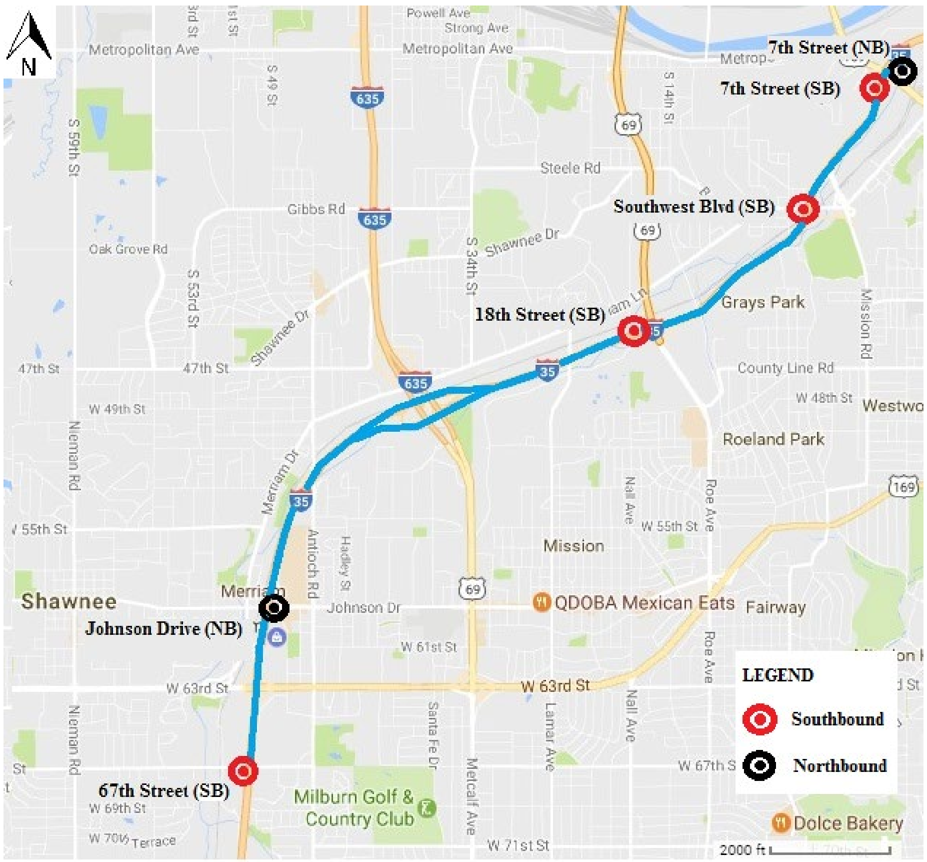


Figure 3.1: I-35 N and I-35 S Locations of Ramp Meters

3.2 Sensor Data Collection

Traffic volume, occupancy, and speed data at the mainline were obtained from the KC Scout Portal (http://www.kcscout.net/KcDataPortal). Weekdays (excluding holidays) were considered for this analysis, and the data were obtained from July 1, 2015, to December 31, 2015, for the "before" analysis. The ramp meters were activated at all locations on July 28, 2021, but following discussions with KC Scout, this study omitted the first two months of meter data for the "after" analysis to ensure driver acclimation to the new system. Therefore, the data collection period was October 1, 2021, to February 28, 2022, except for the location at I-35 N @ 7th St. Trfy., which utilized the March 2022 data instead of the November 2021 data due to very low quality of speed data at that time. The daily periods when the ramp meters were operational were the analysis periods. Based on ramp metering specifications, ramp meters were active 7:00–9:00 a.m. and 4:00–6:00 p.m. or 6:30 p.m., depending on the location. Therefore, the selected analysis periods were 7:00–9:00 a.m. and 4:00–7:00 p.m. All data were obtained in 15-minute intervals. Table 3.1 presents the descriptions and coordinates of the junctions at each location, as well as the name and identification numbers of corresponding KC Scout detectors along the mainline.

Table 3.1: Study Sites

Location Description	Coordinates	Freeway Detector ID	Evaluation Periods
I-35 S @ 7th St. Trfy.	39.069224, -94.619852	Upstream: I-35 S @ 7th St. Trfy.	Before: 7/1/2015–12/31/2015 After: 10/1/2021–2/28/2022
I-35 S @ Southwest Blvd.	39.055887, -94.630409	Upstream: I-35 S @ North of Mill St. Downstream: I-35 S @ North of Roe Ave.	Before: 7/1/2015–12/31/2015 After: 10/1/2021–2/28/2022
I-35 S @ 18th St. Expy.	39.046843, -94.650225	Upstream: I-35 S @ North of 18th St. Expy.	Before: 7/1/2015–12/31/2015 After: 10/1/2021–2/28/2022
I-35 S @ 67th St.	39.005444, -94.694321	Upstream: I-35 S @ 67th St.	Before: 7/1/2015–12/31/2015 After: 10/1/2021–2/28/2022
I-35 N @ 7th St. Trfy.	39.073905, -94.615641	Upstream: I-35 N @ 7th St. Trfy.	Before: 7/1/2015–12/31/2015 After: 10/1/2021–10/31/2021, 1/12/2021–3/31/2022
I-35 N @ Johnson Dr.	39.025117, -94.691000	Upstream: I-35 N @ Johnson Dr.	Before: 7/1/2015–12/31/2015 After: 10/1/2021–2/28/2022

These sensors were selected because they are near the merge junctions and because they had readily available traffic data. In the case of I-35 S @ Southwest Blvd., both mainline sensors directly upstream and directly downstream of the merge junction were considered, due to their proximity to the ramps. Ramp detector data at all junctions were not available for the "before" period, so these data were not obtained for the "after" period. The exact positions of the detectors at the locations studied are shown in Figures 3.2 through 3.6.

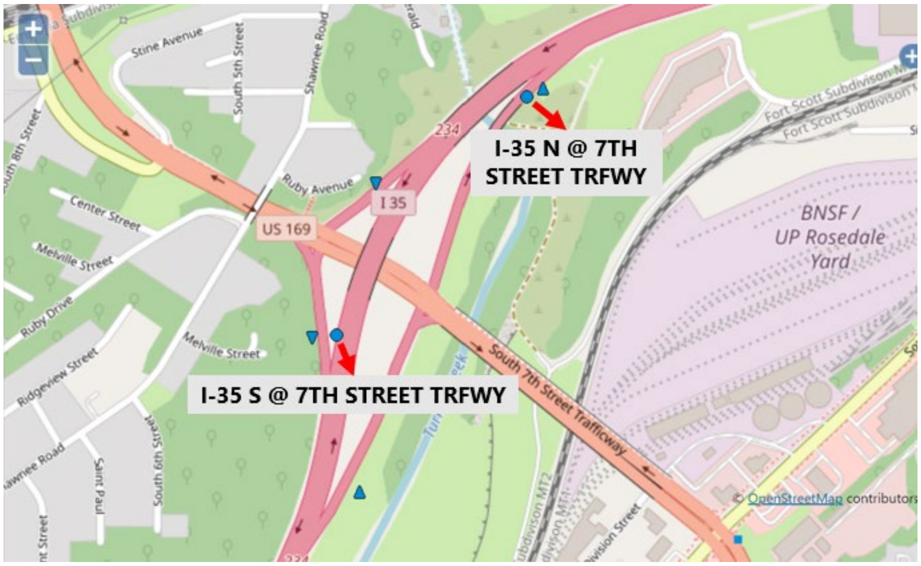


Figure 3.2: Locations of Detectors Along I-35 at 7th St. Trfy.

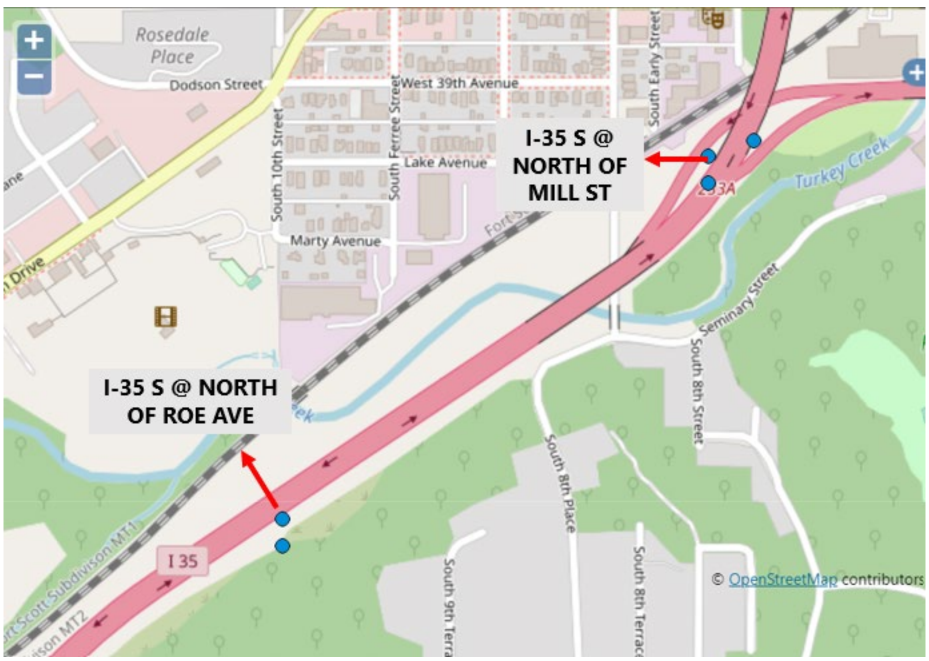


Figure 3.3: Locations of Detectors Along I-35 S at Southwest Blvd.

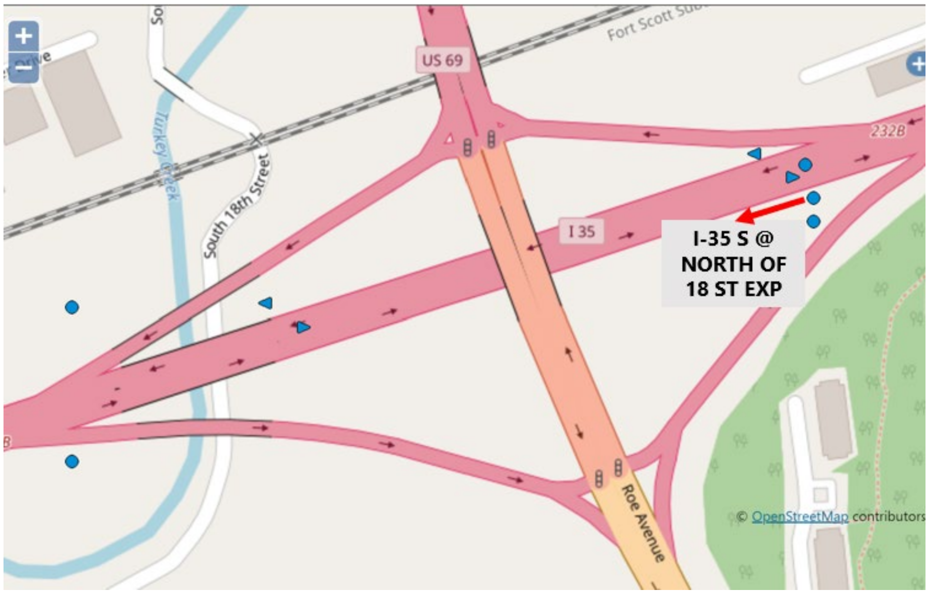


Figure 3.4: Locations of Detectors Along I-35 S at 18th St. Expy.

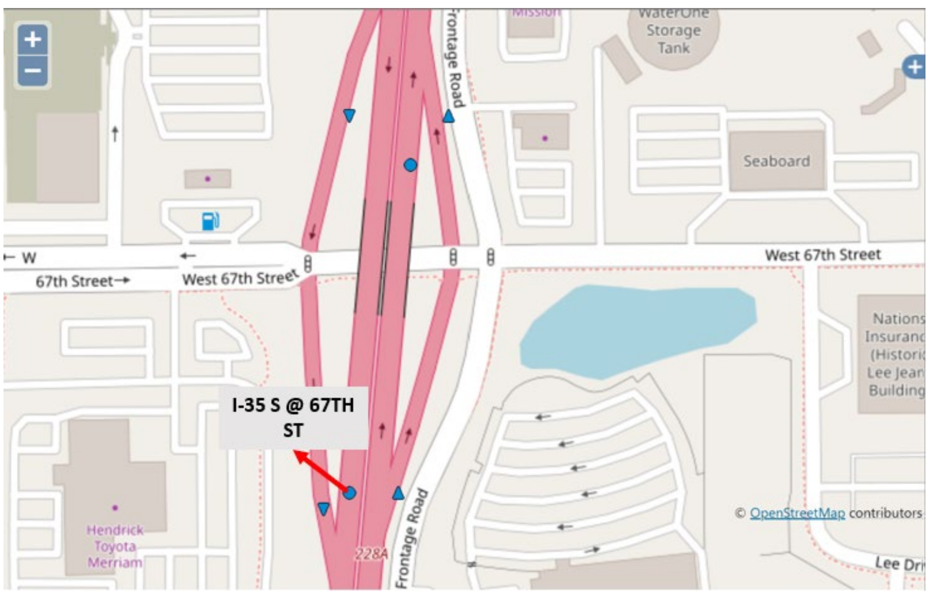


Figure 3.5: Locations of Detectors Along I-35 S at 67th St.

Figure 3.6: Locations of Detectors Along I-35 N at Johnson Dr.

3.3 Crash Data Collection

Crash data were obtained for both directions of I-35 from the Kansas Department of Transportation (KDOT) for both study periods. The crash data included

- Date and time;
- Accident key;
- State, county milepost, and city;
- Road name and direction;
- Proximity to interchange or other road;
- Crash class (animal, fixed object, other motor vehicle, other non-collision, other object, overturned, parked motor vehicle);
- Crash type (rear-end, sideswipe, angle, head-on, other);
- Type of fixed object, if applicable (median barrier, guardrail, bridge rail, crash cushion, barricade, curb, ditch, sign post, other post/pole);
- KABCO injury classification (number of vehicles, fatalities, injuries, property-damage only [PDO]);
- Weather and lighting conditions; and
- Latitude and longitude.

The research team used crash data coordinates for the entire I-35 corridor to identify the exact crash locations and determine if they occurred near the ramp merge junction. A 1-mile radius, measured from the junction's gore point, was used to estimate the influence area of the merge, and only crashes located within the 1-mile radius were analyzed. All remaining crashes were excluded. In addition, crash data that occurred only during the ramp metering periods (7:00–9:00 a.m. and 4:00–7:00 p.m.) were analyzed. Figure 3.7 illustrates all crash records obtained from the 2015 and 2021/2022 data, crash locations, and the radii of the junction influence areas. The ArcGIS tool was used to create the figure and to analyze the crashes that occurred within the 1-mile radius during the analysis periods. For the locations at I-35 S @ 7th St. Trfy., Southwest Blvd., and 18th St. Expy., the overlap was eliminated by reducing the length of the common segments and not double-counting the number of crashes.

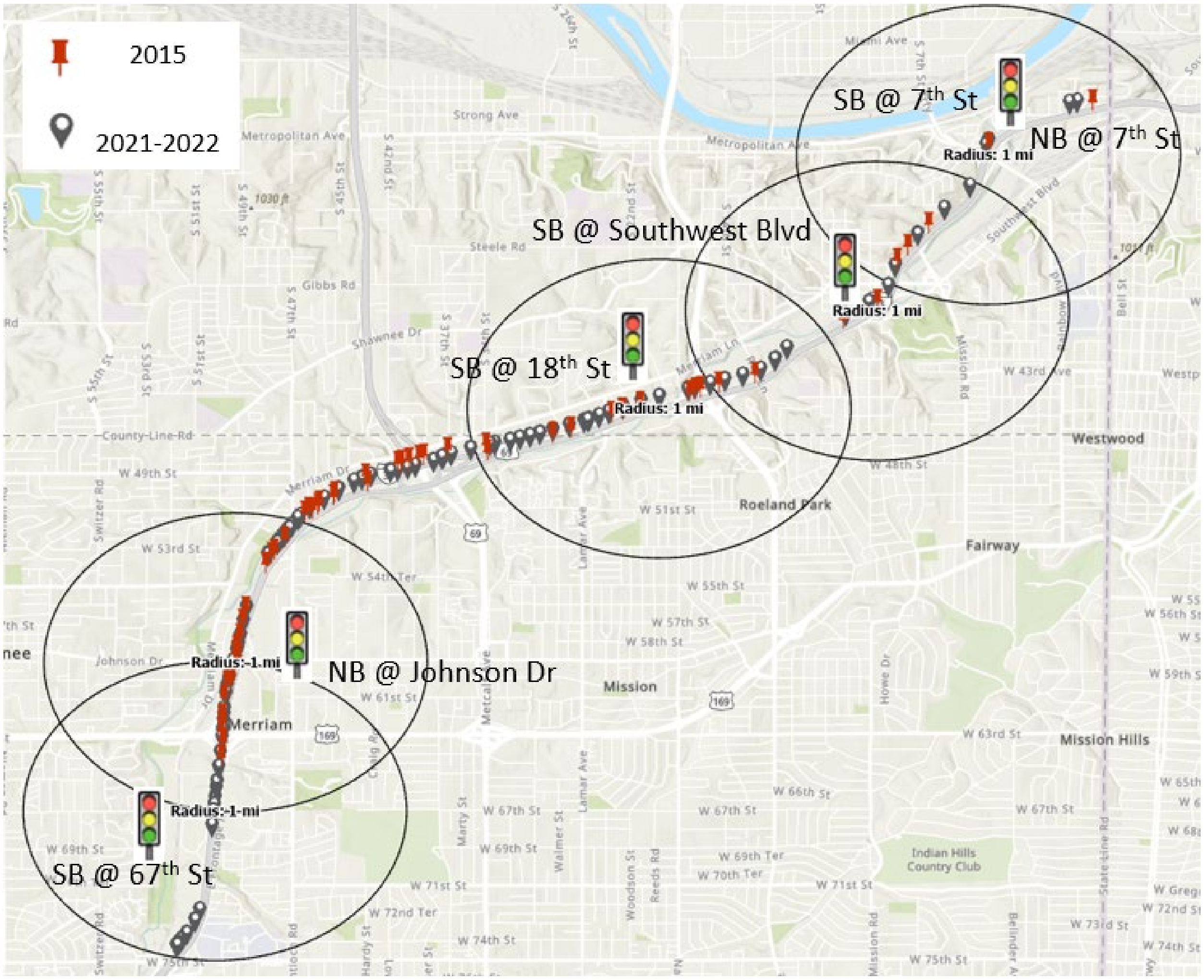


Figure 3.7: Crash Data Locations

3.4 Ramp Metering Data Collection

In addition to traffic and crash data, the ramp metering settings during the "after" period (October 2021–February 2022) were also obtained from KC Scout. As shown in Tables 3.2 and 3.3, the ramp metering rates for the entire study corresponded to each of the two lanes on each on-ramp (except at the 67th St. junction, which only has one lane on the on-ramp). KC Scout uses a traffic-responsive occupancy-based ramp metering algorithm that selects ramp rates so that the mainline occupancies remain below specific thresholds. For the southbound locations (Table 3.2), the occupancy thresholds to trigger each ramp metering rate are based on the occupancy measurements at the mainline lanes 2 and 3.

Table 3.2: Ramp Metering Settings at I-35 S Locations

Level	Ramp Metering Rate (veh/h/ln)	Mainline Occupancy Threshold (%)
I-35 S @ Southwest Blvd.		
1	450	12
2	360	14
3	330	16
4	300	18
5	270	20
6	270	22
I-35 S @ 18th St. Expy.		
1	420	12
2	360	13
3	300	14
4	270	16
5	240	18
6	210	20
I-35 S @ 7th St. Trfy.		
1	420	10
2	360	11
3	300	13
4	270	15
5	240	17
6	210	19
I-35 S @ 67th St.		
1	420	13
2	360	15
3	300	19
4	270	23
5	240	27
6	210	31

For the northbound locations shown in Table 3.3, the occupancy thresholds to trigger each ramp metering rate are based on occupancy measurements at mainline lanes 1–4 (I-35 N @ Johnson Dr.) and lanes 1–3 (I-35 N @ 7th St. Trfy.).

Table 3.3: Ramp Metering Settings at I-35 N Locations

Level	Ramp Metering Rate (veh/h/ln)	Mainline Occupancy Threshold (%)
I-35 N @ Johnson Dr.		
1	720	15
2	540	17
3	480	19
4	450	21
5	420	23
6	390	25
I-35 N @ 7th St. Trfy.		
1	720	15
2	420	17
3	390	19
4	360	21
5	330	23
6	300	25

In addition to the ramp metering settings, KC Scout provided detailed logs of their system during the study period, including the actual ramp metering activation and termination, the requested ramp metering rate based on the algorithm, the effective rate (actual ramp flow rate), the number of red violations, and the per-lane mainline detector data (speed, flow rate, and occupancy). Due to a software glitch, the detailed log was available only after February 2022 or August 2022 at the following locations: I-35 N @ 7th St. Trfy., I-35 N @ Johnson Dr., I-35 S @ 7th St. Trfy., and I-35 S @ 67th St. However, since the actual ramp metering rates were not needed for analysis, the analysis continued without adjusting the "after" period dates to account for the unavailable data.

Chapter 4: Data Analysis

4.1 Safety Analysis

The crash data along I-35 were analyzed to investigate the number of crashes that occurred within the influence area as a function of crash type (rear-end, sideswipe, and angle-side impact). These crash types commonly occur at freeway merge segments. Table 4.1 presents the total number of crashes by type during the two 5-month periods.

Table 4.1: Comparison of Crash Frequency by Type

Location	Before			After			% Reduction
	Rear-End	Sideswipe	Angle-Side Impact	Rear-End	Sideswipe	Angle-Side Impact	
I-35 S @ 67th St.	17	2	1	6	2	0	60.0%
I-35 S @18th St. Expy.	15	2	0	3	0	0	82.4%
I-35 S @ Southwest Blvd.	5	0	0	2	0	0	60.0%
I-35 S @ 7th St. Trfy.	6	0	0	0	1	0	83.3%
I-35 N @ Johnson Dr.	25	6	0	10	2	2	54.8%
I-35 N @ 7th St. Trfy.	0	0	1	0	0	1	0.0%
Total	**68**	**10**	**2**	**21**	**5**	**3**	**63.8%**

Table 4.1 shows a clear decrease in the number of crashes at most locations. For example, the number of rear-end crashes decreased by approximately 69%, and the number of sideswipe crashes decreased by 50%. Although the number of angle-side impact crashes increased by 50%, the absolute value is very small (increase by 1 crash). Most of the sites had significant crash frequency reductions, ranging from 54.8% to 83.3%, except for the location at I-35 N @ 7th St. Trfy, where safety levels remained unchanged. Illustrative graphs showing the safety analysis results are presented in the Appendix.

Table 4.2 presents the KABCO injury classification (number of vehicles, fatalities, injuries, PDO) and the percent change for all locations. The results indicate clear reductions in the number of vehicles involved, total crashes, fatal crashes, injury crashes, PDO crashes, and number of injuries in all cases. The number of deaths remained unchanged because it was already zero.

Table 4.2: Comparison of Crashes Based on Injury Classification

Location	# of Vehicles	Total Crashes	Fatal Crashes	Injury Crashes	PDO Crashes	# of Deaths	# of Injuries
I-35 S @ 67th St. - Before	45	20	0	4	16	0	5
I-35 S @ 67th St. - After	18	8	0	0	8	0	0
Reduction	60.0%	60.0%	-	100.0%	50.0%	-	100.0%
I-35 S @ 18th St. Expy. - Before	41	17	0	7	10	0	13
I-35 S @ 18th St. Expy. - After	8	3	0	1	2	0	1
Reduction	80.5%	82.4%	-	85.7%	80.0%	-	92.3%
I-35 S @ Southwest Blvd. - Before	16	5	0	2	3	0	4
I-35 S @ Southwest Blvd. - After	5	2	0	0	2	0	0
Reduction	68.8%	60.0%	-	100.0%	33.3%	-	100.0%
I-35 S @ 7th St. Trfy. - Before	13	6	0	1	5	0	1
I-35 S @ 7th St. Trfy. - After	2	1	0	0	1	0	0
Reduction	84.6%	83.3%	-	100.0%	80.0%	-	100.0%
I-35 N @ Johnson Dr. - Before	71	31	0	7	24	0	9
I-35 N @ Johnson Dr. - After	29	14	0	2	12	0	2
Reduction	59.2%	54.8%	-	71.4%	50.0%	-	77.8%
I-35 N @ 7th St. Trfy. - Before	2	1	0	1	0	0	1
I-35 N @ 7th St. Trfy. - After	2	1	0	0	1	0	0
Reduction	0.0%	0.0%	-	100.0%	- 100%	-	100.0%

Because of the variability in flow rates and exposure between the two periods of analysis, the crash frequency was further analyzed to obtain crash rates. The crash rate for each segment was calculated using Equation 4.1.

$$\boldsymbol{R = \frac{1{,}000{,}000 * C}{365 * N * V * L}}$$

Equation 4.1

Where:

R = crash rate for the road segment expressed as crashes per 100 million vehicle-miles of travel (VMT),

C = total number of crashes in the study period,

N = number of years of data,

V = number of vehicles per day (both directions), and

L = length of roadway segment in miles.

The final crash rates for each segment are presented in Table 4.3, which shows a decrease in crash rates at all locations except the I-35 N @ 7th St. Trfy. location, which showed a slight increase in crash rate due to a reduction in exposure (flow rates). All remaining segments showed crash rates that decreased by 13%–82.5% due to implementation of ramp metering.

Table 4.3: Comparison of Crash Rates

Location	Before	After	% Reduction
I-35 S @ 67th St.	0.38	0.17	55.9%
I-35 S @ 18th St. Expy.	0.65	0.11	82.5%
I-35 S @ Southwest Blvd.	0.29	0.25	13.0%
I-35 S @ 7th St. Trfy.	0.28	0.07	73.4%
I-35 N @ Johnson Dr.	0.64	0.29	54.7%
I-35 N @ 7th St. Trfy.	0.12	0.13	-5.8%
Total	2.36	1.03	56.4%

4.2 Traffic Operational Analysis

For the traffic analysis, this study investigated how average speeds and flow rates were impacted by ramp metering. All flow rate data were aggregated to 15-minute intervals, while average speed data were calculated considering volume-weighted averages. Since the data were obtained from field sensors, the quality of the sensor data was also taken into consideration. Data with very low quality (less than 70%) were removed from consideration. A summary table of the percentage of data with acceptable quality (70% or more) for all locations is shown in Table 4.4. As shown, most of the data during the analysis period were utilized in this study except for data from the I-35 N @ Johnson Dr. location during the "after" period, where approximately 33% of the data were not analyzed due to low quality. Detailed analysis of each segment is presented in the following sections, and figures showing speed improvements at selected locations are presented in the Appendix.

Table 4.4: Data Quality Results

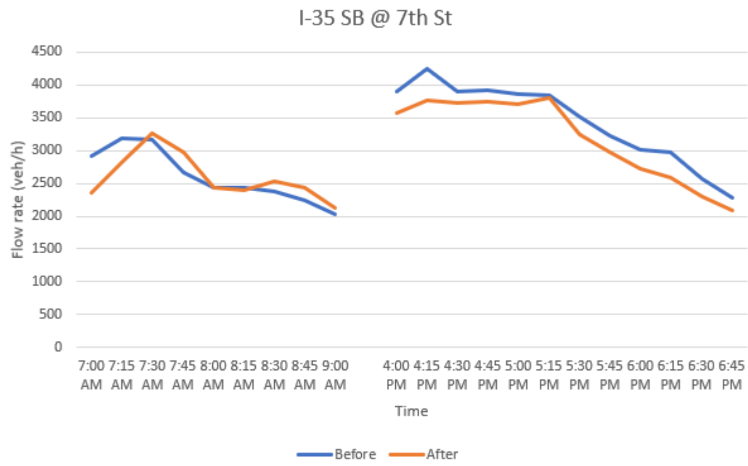
Location	Before	After
I-35 S @ 67th St.	99.1%	99.8%
I-35 S @18th St. Expy.	98.9%	99.5%
I-35 S @ Southwest Blvd.	98.7%	99.6%
I-35 S @7th St. Trfy.	98.0%	97.9%
I-35 N @ Johnson Dr.	99.6%	99.1%
I-35 N @ 7th St. Trfy.	99.4%	77.0%

4.2.1 I-35 S @ 7th St. Trfy.

Table 4.5 and Figure 4.1 summarize the average flow rates and speeds during the morning and afternoon peak periods for the 5-month time periods before and after deployment of the ramp metering. Table 4.6 shows the results of two sample one-way t-tests with a null hypothesis of the difference in mean flows or speeds as zero, and the alternative hypothesis is that their difference is negative (i.e., speeds or flows increased).

Table 4.5: Flow Rate and Speed Comparison at I-35 S @ 7th St. Trfy.

	Flow Rate (veh/h)			Speed (mi/h)		
Time	Before	After	% Increase	Before	After	% Increase
7:00 AM	2916.64	2356.03	-19.2%	63.47	64.45	1.5%
7:15 AM	3182.79	2816.57	-11.5%	62.94	63.95	1.6%
7:30 AM	3166.79	3261.72	3.0%	62.82	63.19	0.6%
7:45 AM	2667.24	2979.37	11.7%	62.60	63.29	1.1%
8:00 AM	2437.27	2429.07	-0.3%	62.46	63.59	1.8%
8:15 AM	2426.65	2398.47	-1.2%	62.70	63.71	1.6%
8:30 AM	2374.40	2523.48	6.3%	62.63	63.65	1.6%
8:45 AM	2243.50	2428.02	8.2%	62.70	63.77	1.7%
9:00 AM	2035.62	2118.32	4.1%	62.77	63.18	0.6%
4:00 PM	3902.51	3579.10	-8.3%	60.15	62.63	4.1%
4:15 PM	4248.86	3761.62	-11.5%	53.66	61.61	14.8%
4:30 PM	3901.21	3736.67	-4.2%	47.93	61.37	28.0%
4:45 PM	3918.21	3749.37	-4.3%	40.50	58.65	44.8%
5:00 PM	3853.11	3700.35	-4.0%	42.36	58.76	38.7%
5:15 PM	3848.56	3802.82	-1.2%	37.56	54.36	44.7%
5:30 PM	3516.89	3250.85	-7.6%	42.91	59.63	39.0%
5:45 PM	3221.53	2966.16	-7.9%	54.67	62.67	14.6%
6:00 PM	3011.17	2724.49	-9.5%	58.71	63.81	8.7%
6:15 PM	2969.14	2598.23	-12.5%	59.54	63.86	7.2%
6:30 PM	2563.29	2307.16	-10.0%	61.49	63.65	3.5%
6:45 PM	2273.67	2091.88	-8.0%	62.65	63.72	1.7%



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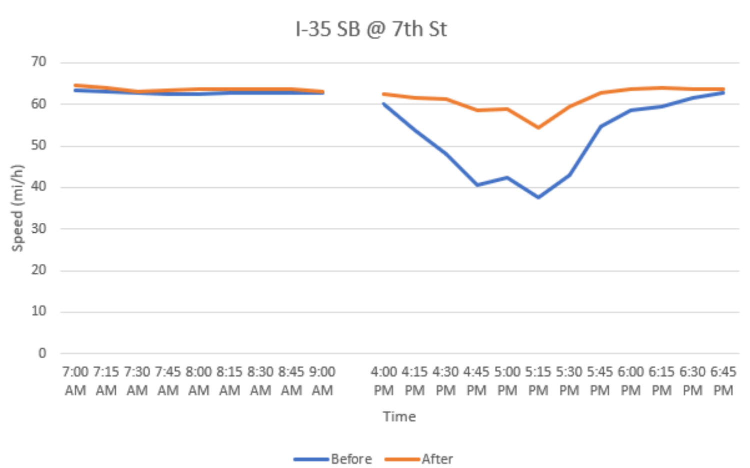


(b)

Figure 4.1: I-35 S @ 7th St. Trfy.: (a) Flow Rate and (b) Speed Comparison

Analysis results show that, although flow rates were somewhat unchanged or slightly reduced at the I-35 S @ 7th St. Trfy. location, the difference is not statistically significant at 95% confidence level ($\alpha = 0.05$). However, the speeds significantly improved after the deployment of ramp metering during the afternoon peak period. Before the ramp metering deployment, this segment experienced recurring congestion, but after the ramp metering deployment, speeds significantly increased (20% on average during the afternoon peak). Table 4.6 summarizes these findings.

Table 4.6: Hypothesis Testing at I-35 S @ 7th St. Trfy.

Sample	N	Mean	StDev	SE Mean	T-value	DF	P-value
AM Flow Before	9	2606	406	135			
AM Flow After	9	2590	358	119	0.09	15	0.534
PM Flow Before	12	3436	620	179			
PM Flow After	12	3189	628	181	0.97	21	0.828
AM Speed Before	9	62.788	0.291	0.097			
AM Speed After	9	63.642	0.406	0.14	-5.13	14	<0.001*
PM Speed Before	12	51.84	9.12	2.6			
PM Speed After	12	61.23	2.90	0.84	-3.40	13	0.002*

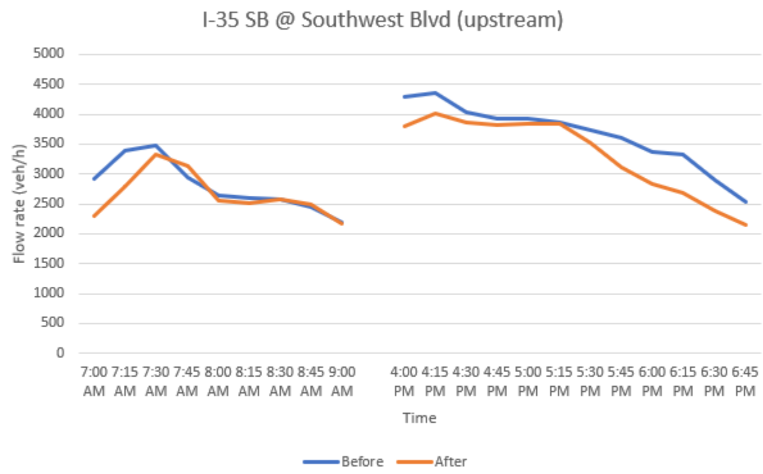
* Statistically significant at 95% confidence level

4.2.2 I-35 S @ Southwest Blvd.

Table 4.7 and Figure 4.2 summarize the average flow and speed at the upstream detector at I-35 S @ Southwest Blvd., while Table 4.8 and Figure 4.3 show the average flow and speeds at the downstream detector. The results at both locations are similar, with a slight decrease in observed flow rates at both locations. However, speed reductions during the afternoon peak periods improved after ramp metering was deployed.

Table 4.7: Flow Rate and Speed Comparison at I-35 S @ Southwest Blvd. (Upstream)

	Flow Rate (veh/h)			Speed (mi/h)		
Time	Before	After	% Increase	Before	After	% Increase
7:00 AM	2909.04	2302.81	-20.8%	62.10	59.03	-5.0%
7:15 AM	3401.00	2801.13	-17.6%	61.81	58.82	-4.8%
7:30 AM	3487.26	3317.87	-4.9%	60.52	58.25	-3.8%
7:45 AM	2949.07	3127.90	6.1%	60.25	57.60	-4.4%
8:00 AM	2643.66	2561.76	-3.1%	60.58	58.77	-3.0%
8:15 AM	2604.68	2506.10	-3.8%	60.96	58.71	-3.7%
8:30 AM	2576.16	2577.93	0.1%	61.69	58.38	-5.4%
8:45 AM	2457.20	2480.08	0.9%	61.27	58.78	-4.1%
9:00 AM	2191.72	2168.95	-1.0%	61.52	58.87	-4.3%
4:00 PM	4301.57	3796.06	-11.8%	53.83	55.45	3.0%
4:15 PM	4347.54	4023.16	-7.5%	34.43	47.25	37.2%
4:30 PM	4034.52	3860.51	-4.3%	28.06	43.32	54.4%
4:45 PM	3931.22	3820.58	-2.8%	26.16	35.07	34.0%
5:00 PM	3924.41	3830.97	-2.4%	27.64	38.70	40.0%
5:15 PM	3866.04	3847.30	-0.5%	26.17	35.46	35.5%
5:30 PM	3727.88	3523.87	-5.5%	29.24	44.15	51.0%
5:45 PM	3603.46	3106.87	-13.8%	39.14	54.51	39.3%
6:00 PM	3360.94	2825.15	-15.9%	52.32	56.72	8.4%
6:15 PM	3335.69	2690.17	-19.4%	56.54	56.95	0.7%
6:30 PM	2893.05	2381.11	-17.7%	58.71	57.35	-2.3%
6:45 PM	2530.06	2150.57	-15.0%	60.65	57.72	-4.8%



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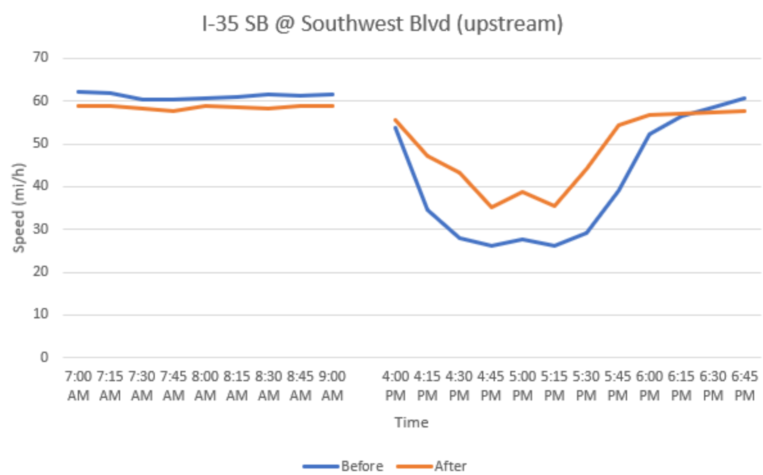
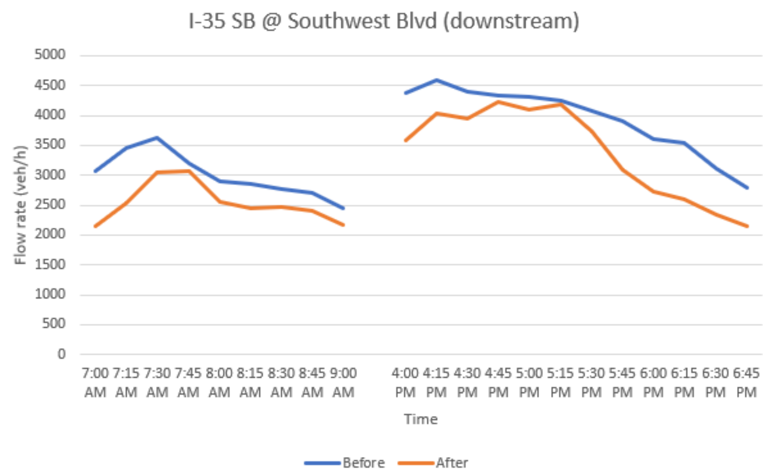


(b)

Figure 4.2: I-35 S @ Southwest Blvd. (Upstream): (a) Flow Rate and (b) Speed Comparison

Table 4.8: Flow Rate and Speed Comparison at I-35 S @ Southwest Blvd. (Downstream)

	Flow Rate (veh/h)			Speed (mi/h)		
Time	Before	After	% Increase	Before	After	% Increase
7:00 AM	3068.59	2140.10	-30.3%	64.41	65.35	1.5%
7:15 AM	3464.75	2539.35	-26.7%	63.68	64.97	2.0%
7:30 AM	3636.07	3048.41	-16.2%	61.90	64.04	3.5%
7:45 AM	3205.35	3069.12	-4.3%	62.13	62.85	1.2%
8:00 AM	2897.94	2557.02	-11.8%	63.06	64.25	1.9%
8:15 AM	2851.38	2453.75	-13.9%	63.50	64.67	1.8%
8:30 AM	2779.61	2463.46	-11.4%	63.99	64.94	1.5%
8:45 AM	2704.01	2410.43	-10.9%	64.26	65.20	1.5%
9:00 AM	2439.02	2167.00	-11.2%	64.56	65.18	1.0%
4:00 PM	4387.17	3580.12	-18.4%	57.56	60.74	5.5%
4:15 PM	4597.03	4037.21	-12.2%	46.55	55.12	18.4%
4:30 PM	4401.68	3948.56	-10.3%	43.96	53.62	22.0%
4:45 PM	4324.92	4229.45	-2.2%	41.21	48.65	18.1%
5:00 PM	4320.20	4098.83	-5.1%	41.38	51.03	23.3%
5:15 PM	4239.51	4174.40	-1.5%	39.66	48.64	22.6%
5:30 PM	4079.98	3742.12	-8.3%	41.37	52.75	27.5%
5:45 PM	3894.86	3082.43	-20.9%	46.86	59.60	27.2%
6:00 PM	3597.83	2720.45	-24.4%	56.23	62.59	11.3%
6:15 PM	3540.93	2607.92	-26.3%	59.72	62.89	5.3%
6:30 PM	3116.69	2350.30	-24.6%	61.38	63.73	3.8%
6:45 PM	2783.91	2143.81	-23.0%	63.05	63.68	1.0%



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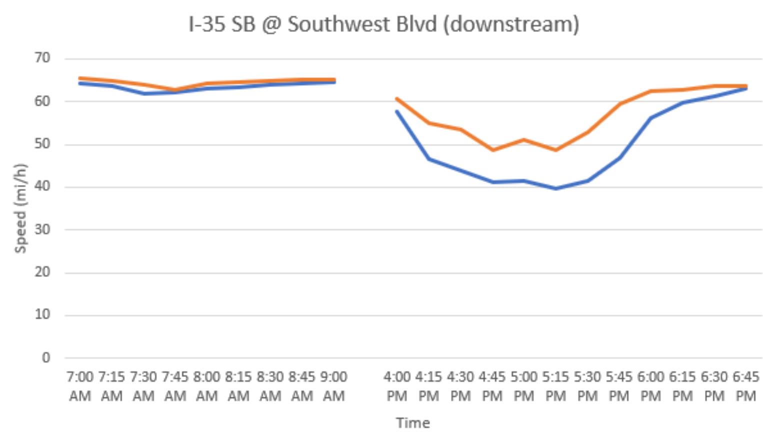


(b)

Figure 4.3: I-35 S @ Southwest Blvd. (Downstream): (a) Flow Rate and (b) Speed Comparison

Hypothesis testing at the upstream station revealed that flow rates were unchanged and speeds slightly decreased during the morning peak period although conditions remained uncongested. However, speeds significantly increased (24.7% on average) during the afternoon peak period while demand remained the same, indicating that the ramp metering positively affected traffic operations. At the downstream location, the flow rates decreased (overall flow rate reduction of 15%) and speeds increased during both peak periods. Although the largest speed increase (15.5% on average) occurred during the afternoon peak period, the speed increase could be a result of decreased demand, ramp metering deployment, or both (Table 4.9).

Table 4.9: Hypothesis Testing at I-35 S @ Southwest Blvd.

Sample	N	Mean	StDev	SE Mean	T-value	DF	P-value
AM Flow Before (Upstream)	9	2802	428	143			
AM Flow After (Upstream)	9	2649	373	124	0.807	16	0.2157
PM Flow Before (Upstream)	12	3655	546	158			
PM Flow After (Upstream)	12	3321	659	190	1.349	22	0.096
AM Speed Before (Upstream)	9	61.19	0.65	0.22			
AM Speed After (Upstream)	9	58.58	0.44	0.15	10.034	16	<0.001*
PM Speed Before (Upstream)	12	41.07	14.16	4.10			
PM Speed After (Upstream)	12	48.55	8.95	2.60	-1.547	22	0.068
AM Flow Before (Downstream)	9	3005	379	126			
AM Flow After (Downstream)	9	2539	329	110	2.785	16	0.007*
PM Flow Before (Downstream)	12	3940	567	164			
PM Flow After (Downstream)	12	3393	769	222	1.985	22	0.030*
AM Speed Before (Downstream)	9	63.50	0.96	0.32			
AM Speed After (Downstream)	9	64.61	0.79	0.26	-2.666	16	0.008*
PM Speed Before (Downstream)	12	49.91	8.95	2.60			
PM Speed After (Downstream)	12	56.92	5.91	1.70	-2.263	22	0.017*

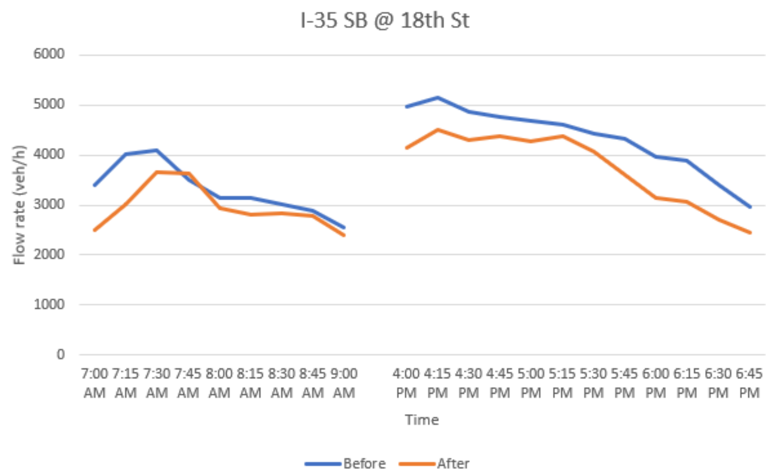
* Statistically significant at 95% confidence level

4.2.3 I-35 S @ 18th St. Expy.

Table 4.10 and Figure 4.4 summarize the average flow and speed at the 18th St. Expy. detector. As shown, traffic flow and speeds were similar in the "before" and "after" morning peak analysis periods, while flow decreased but speeds increased in the afternoon peak periods after the ramp meters were deployed.

Table 4.10: Flow Rate and Speed Comparison at I-35 S @ 18th St. Expy.

	Flow Rate (veh/h)			Speed (mi/h)		
Time	Before	After	% Increase	Before	After	% Increase
7:00 AM	3393.09	2500.35	-26.3%	64.95	65.35	0.6%
7:15 AM	4014.17	3020.34	-24.8%	63.77	64.99	1.9%
7:30 AM	4104.09	3657.58	-10.9%	61.46	63.50	3.3%
7:45 AM	3501.51	3634.43	3.8%	61.45	60.51	-1.5%
8:00 AM	3132.57	2937.26	-6.2%	63.38	63.65	0.4%
8:15 AM	3131.66	2811.85	-10.2%	64.51	64.58	0.1%
8:30 AM	3021.64	2827.03	-6.4%	64.88	64.94	0.1%
8:45 AM	2874.37	2786.20	-3.1%	64.57	65.05	0.7%
9:00 AM	2539.21	2404.97	-5.3%	64.67	65.11	0.7%
4:00 PM	4958.60	4141.02	-16.5%	59.41	61.34	3.2%
4:15 PM	5154.03	4498.23	-12.7%	49.99	55.57	11.2%
4:30 PM	4862.38	4295.98	-11.6%	46.12	54.24	17.6%
4:45 PM	4764.73	4390.56	-7.9%	41.39	51.24	23.8%
5:00 PM	4678.31	4268.82	-8.8%	40.74	52.50	28.9%
5:15 PM	4610.31	4384.92	-4.9%	39.84	49.98	25.4%
5:30 PM	4423.56	4070.54	-8.0%	41.40	52.60	27.1%
5:45 PM	4321.62	3593.56	-16.8%	46.22	58.47	26.5%
6:00 PM	3974.40	3150.19	-20.7%	54.84	62.16	13.3%
6:15 PM	3890.27	3059.55	-21.4%	59.70	62.66	5.0%
6:30 PM	3394.50	2702.97	-20.4%	62.08	63.34	2.0%
6:45 PM	2972.91	2456.99	-17.4%	63.45	63.80	0.5%



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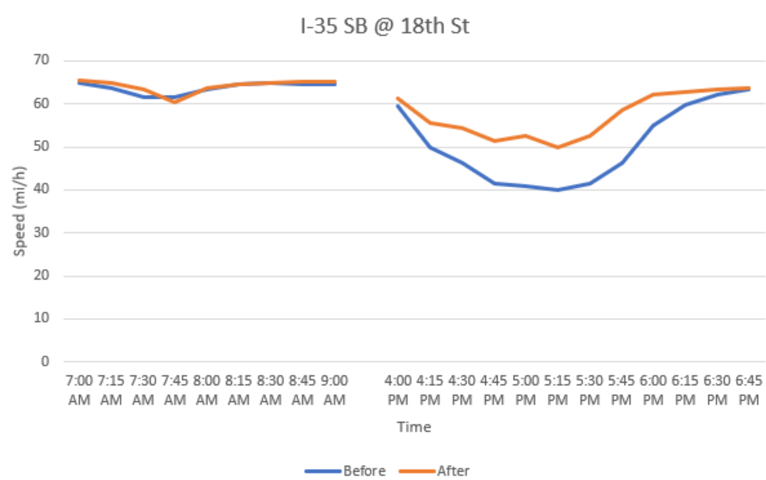


(b)

Figure 4.4: I-35 S @ 18th St. Expy: (a) Flow Rate and (b) Speed Comparison

Based on the statistical analysis (Table 4.11), the afternoon speeds and flow rates significantly changed after the ramp meters were deployed. Speeds increased by 15.4%, and flow rates decreased by 13.9%. However, it is not clear if the speed increase was a result of the decrease in the average flow rates or the deployment of the ramp metering algorithm or both.

Table 4.11: Hypothesis Testing at I-35 S @ 18th St. Expy.

Sample	N	Mean	StDev	SE Mean	T-value	DF	P-value
AM Flow Before	9	3301	512	171			
AM Flow After	9	2953	438	146	1.549	16	0.070
PM Flow Before	12	4334	660	191			
PM Flow After	12	3751	728	210	2.055	22	0.026*
AM Speed Before	9	63.74	1.39	0.46			
AM Speed After	9	64.19	1.53	0.51	-0.653	16	0.261
PM Speed Before	12	50.43	9.03	2.60			
PM Speed After	12	57.32	5.19	1.50	-2.292	22	0.016*

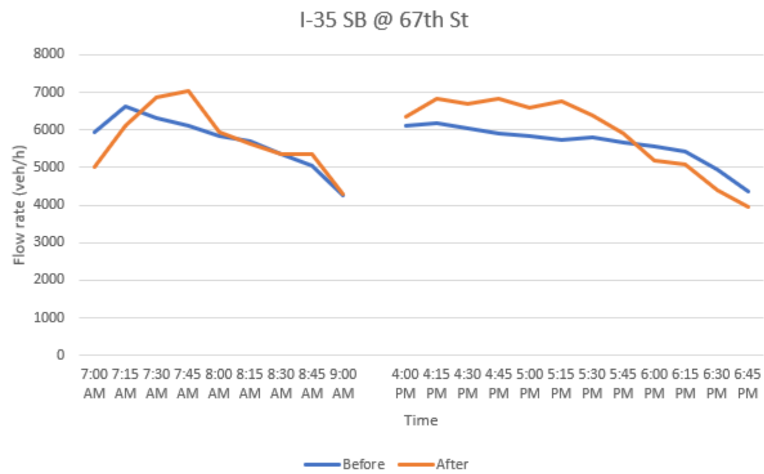
* Statistically significant at 95% confidence level

4.2.4 I-35 S @ 67th St.

Table 4.12 and Figure 4.5 show the flow rates and speeds at the I-35 S @ 67th St. location. As shown, the flow rates in the "before" period were similar to the "after" period, but the speed profiles improved after the ramp metering deployment.

Table 4.12: Flow Rate and Speed Comparison at I-35 S @ 67th St.

	Flow Rate (veh/h)			Speed (mi/h)		
Time	Before	After	% Increase	Before	After	% Increase
7:00 AM	5948.94	5005.50	-15.9%	55.37	60.75	9.7%
7:15 AM	6616.47	6101.18	-7.8%	43.27	59.03	36.4%
7:30 AM	6325.82	6871.67	8.6%	32.63	56.12	72.0%
7:45 AM	6097.83	7044.54	15.5%	29.16	51.12	75.3%
8:00 AM	5850.60	5943.43	1.6%	31.95	53.32	66.9%
8:15 AM	5690.73	5622.84	-1.2%	37.80	57.46	52.0%
8:30 AM	5368.99	5365.50	-0.1%	47.77	58.72	22.9%
8:45 AM	5062.31	5362.62	5.9%	53.53	60.06	12.2%
9:00 AM	4264.52	4299.14	0.8%	57.73	62.22	7.8%
4:00 PM	6113.23	6349.12	3.9%	31.88	59.42	86.4%
4:15 PM	6196.89	6832.26	10.3%	30.14	56.20	86.5%
4:30 PM	6041.31	6710.87	11.1%	29.13	56.23	93.0%
4:45 PM	5919.02	6832.05	15.4%	28.30	54.77	93.5%
5:00 PM	5825.65	6608.85	13.4%	27.05	53.12	96.4%
5:15 PM	5747.31	6775.79	17.9%	26.98	51.37	90.4%
5:30 PM	5786.07	6386.32	10.4%	27.44	53.23	94.0%
5:45 PM	5651.32	5913.61	4.6%	28.95	56.51	95.2%
6:00 PM	5560.82	5192.30	-6.6%	34.37	59.56	73.3%
6:15 PM	5432.86	5079.41	-6.5%	43.08	60.04	39.4%
6:30 PM	4962.03	4398.85	-11.3%	50.97	60.87	19.4%
6:45 PM	4367.63	3962.94	-9.3%	57.80	61.67	6.7%



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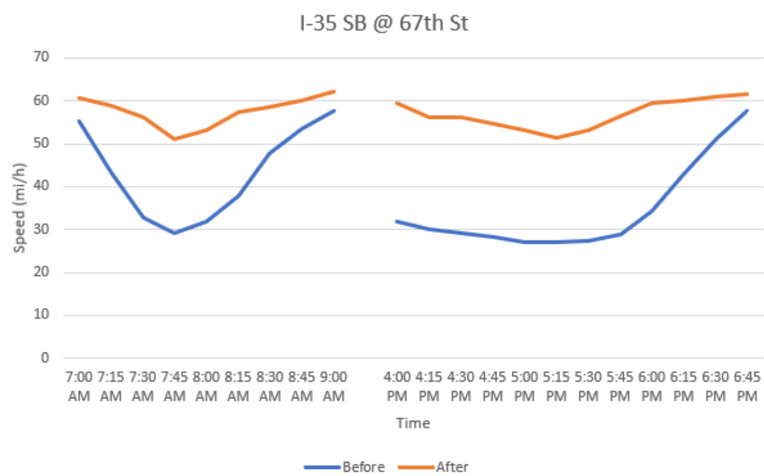


(b)

Figure 4.5: I-35 S @ 67th St.: (a) Flow Rate and (b) Speed Comparison

Statistical analysis revealed that, although the flow rates did not significantly change, the speeds during both the morning and afternoon peak periods significantly increased by 39.5% and 72.8%, respectively. In fact, this site experienced congestion during both peak periods, but the congestion dissipated after the ramp-metering deployment. Incidentally, further south of this site was widened from 3 to 4 lanes in late 2020, therefore, it's possible that the improved traffic operations are attributed to improved geometry, although ramp metering might have helped as well. Table 4.13 summarizes the statistical analysis.

Table 4.13: Hypothesis Testing at I-35 S @ 67th St.

Sample	N	Mean	StDev	SE Mean	T-value	DF	P-value
AM Flow Before	9	5692	712	237			
AM Flow After	9	5735	871	290	-0.116	16	0.455
PM Flow Before	12	5634	519	150			
PM Flow After	12	5920	1013	292	-0.872	22	0.196
AM Speed Before	9	43.25	10.91	3.60			
AM Speed After	9	57.65	3.59	1.20	-3.762	16	<0.001*
PM Speed Before	12	34.67	10.33	3.00			
PM Speed After	12	56.91	3.38	0.98	-7.089	22	<0.001*

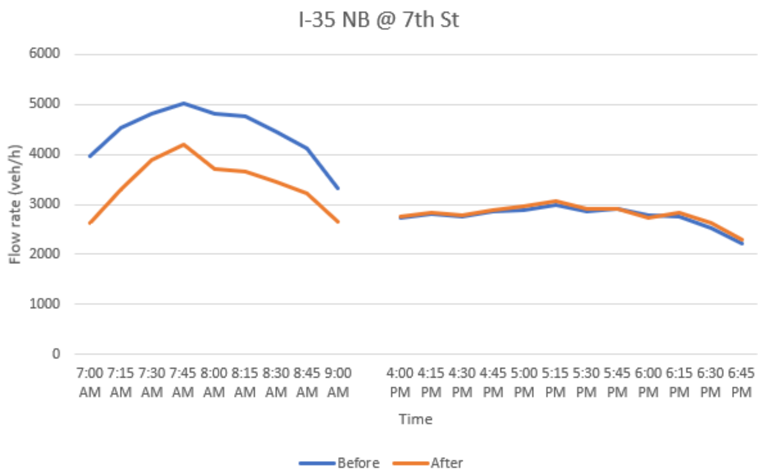
* Statistically significant at 95% confidence level

4.2.5 I-35 N @ 7th St. Trfy.

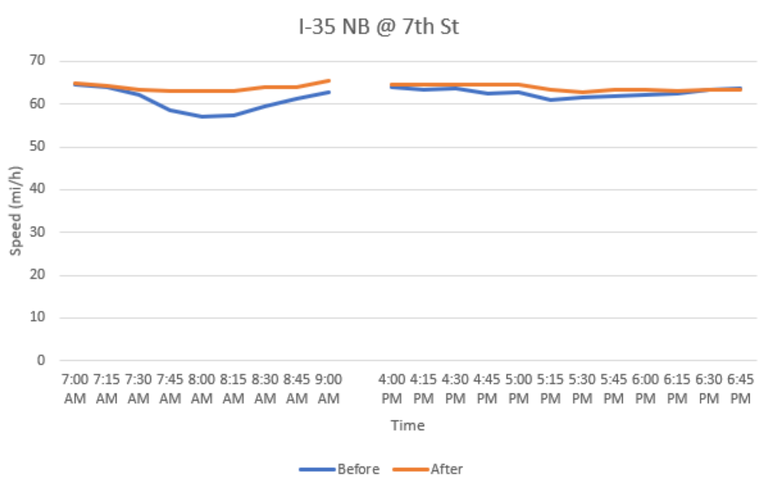
Table 4.14 and Figure 4.6 show the flow rates and speeds at the I-35 N @ 7th St. Trfy. location. As shown, the morning peak flow rates during the "after" period decreased, while the speeds during both the morning and the afternoon peak periods remained uncongested.

Table 4.14: Flow Rate and Speed Comparison at I-35 N @ 7th St. Trfy.

	Flow Rate (veh/h)			Speed (mi/h)		
Time	Before	After	% Increase	Before	After	% Increase
7:00 AM	3953.55	2594.15	-34.4%	64.44	64.93	0.8%
7:15 AM	4532.14	3261.42	-28.0%	64.00	64.13	0.2%
7:30 AM	4817.03	3806.01	-21.0%	62.16	63.48	2.1%
7:45 AM	5024.59	4169.81	-17.0%	58.67	62.94	7.3%
8:00 AM	4803.64	3687.36	-23.2%	57.10	63.16	10.6%
8:15 AM	4767.05	3629.45	-23.9%	57.48	63.06	9.7%
8:30 AM	4454.03	3437.02	-22.8%	59.33	63.84	7.6%
8:45 AM	4121.27	3177.95	-22.9%	61.21	64.04	4.6%
9:00 AM	3311.35	2636.91	-20.4%	62.65	65.56	4.6%
4:00 PM	2726.53	2760.61	1.3%	64.06	64.66	0.9%
4:15 PM	2816.40	2851.38	1.2%	63.41	64.52	1.7%
4:30 PM	2767.18	2800.25	1.2%	63.77	64.65	1.4%
4:45 PM	2851.60	2906.53	1.9%	62.54	64.52	3.2%
5:00 PM	2895.19	2990.07	3.3%	62.63	64.47	2.9%
5:15 PM	2985.12	3082.01	3.2%	61.02	63.39	3.9%
5:30 PM	2870.11	2942.25	2.5%	61.52	62.83	2.1%
5:45 PM	2902.87	2909.13	0.2%	61.97	63.35	2.2%
6:00 PM	2795.27	2701.97	-3.3%	62.09	63.49	2.2%
6:15 PM	2759.43	2823.36	2.3%	62.35	63.18	1.3%
6:30 PM	2513.08	2628.57	4.6%	63.28	63.37	0.1%
6:45 PM	2211.65	2277.15	3.0%	63.62	63.47	-0.2%



(a)



(b)

Figure 4.6: I-35 N @ 7th St. Trfy.: (a) Flow Rate and (b) Speed Comparison

Hypothesis testing revealed a significant drop in the morning peak flows (23.7% on average) but not in the afternoon peak flows. Both peak speeds increased significantly after the ramp metering deployment, but the operational gains were minimal since traffic conditions were already uncongested. In addition, the speed increase (5.3% on average) in the morning peak could be a result of the reduced flow rates or the ramp metering deployment or both. The statistical analysis results are presented in Table 4.15.

Table 4.15: Hypothesis Testing at I-35 N @ 7th St. Trfy.

Sample	N	Mean	StDev	SE Mean	T-value	DF	P-value
AM Flow Before	9	4420	541	180			
AM Flow After	9	3378	523	176	4.157	16	<0.001*
PM Flow Before	12	2758	208	60			
PM Flow After	12	2806	208	58	-0.558	22	0.288
AM Speed Before	9	60.78	2.74	0.91			
AM Speed After	9	63.90	0.88	0.29	-3.250	16	0.003*
PM Speed Before	12	62.69	0.95	0.27			
PM Speed After	12	63.83	0.68	0.20	-3.378	22	0.001*

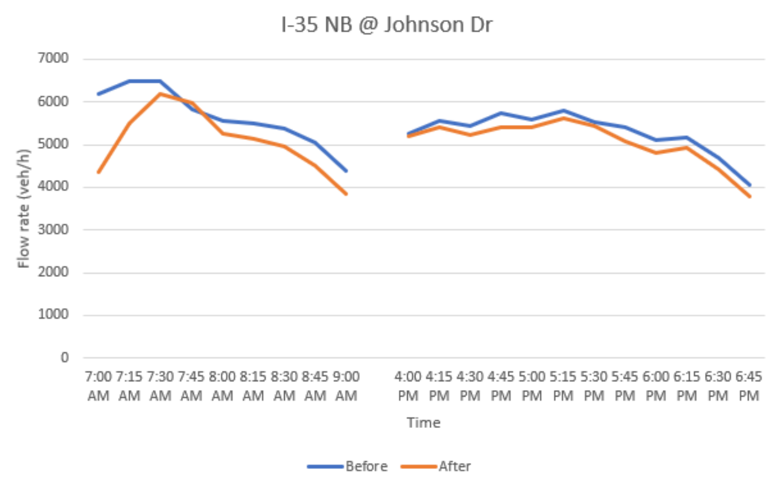
* Statistically significant at 95% confidence level

4.2.6 I-35 N @ Johnson Dr.

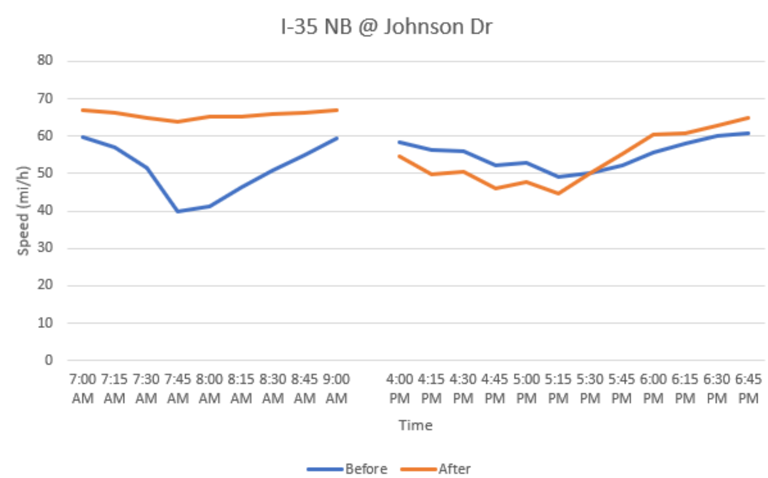
Table 4.16 and Figure 4.7 show the flow rates and speeds at the I-35 N @ Johnson Dr. location. As shown, the flow rates were similar during the "before" and "after" periods for both the morning and afternoon peaks. Speeds during the morning peak congestion improved.

Table 4.16: Flow Rate and Speed Comparison at I-35 N @ Johnson Dr.

	Flow Rate (veh/h)			Speed (mi/h)		
Time	Before	After	% Increase	Before	After	% Increase
7:00 AM	6177.03	4367.09	-29.3%	59.81	67.05	12.1%
7:15 AM	6475.20	5489.12	-15.2%	57.03	66.12	16.0%
7:30 AM	6498.14	6174.46	-5.0%	51.67	64.95	25.7%
7:45 AM	5827.38	5991.09	2.8%	39.97	63.81	59.7%
8:00 AM	5562.25	5258.85	-5.5%	41.18	65.09	58.1%
8:15 AM	5494.89	5151.18	-6.3%	46.50	65.40	40.7%
8:30 AM	5381.08	4953.52	-7.9%	50.67	65.79	29.8%
8:45 AM	5062.24	4521.23	-10.7%	54.77	66.40	21.2%
9:00 AM	4401.56	3860.97	-12.3%	59.36	66.79	12.5%
4:00 PM	5269.33	5182.92	-1.6%	58.23	54.50	-6.4%
4:15 PM	5548.34	5398.87	-2.7%	56.33	49.89	-11.4%
4:30 PM	5436.85	5238.96	-3.6%	55.95	50.39	-9.9%
4:45 PM	5724.58	5422.44	-5.3%	52.32	45.94	-12.2%
5:00 PM	5593.71	5421.44	-3.1%	53.05	47.69	-10.1%
5:15 PM	5797.78	5608.04	-3.3%	48.96	44.76	-8.6%
5:30 PM	5541.49	5442.67	-1.8%	50.28	50.15	-0.3%
5:45 PM	5398.96	5084.84	-5.8%	52.28	55.35	5.9%
6:00 PM	5122.39	4820.63	-5.9%	55.67	60.49	8.7%
6:15 PM	5163.03	4935.18	-4.4%	58.20	60.94	4.7%
6:30 PM	4693.79	4418.49	-5.9%	59.93	62.98	5.1%
6:45 PM	4067.53	3794.67	-6.7%	60.90	64.77	6.4%



(a)



(b)

Figure 4.7: I-35 N @ Johnson Dr.: (a) Flow Rate and (b) Speed Comparison

The statistical analysis showed that the flow rates remained the same, but speeds in the morning peak periods significantly improved by an average of 30.6%. This site used to experience congestion in the morning peak, but after ramp metering deployment, the segment became uncongested. Because the flow rates did not change significantly between the two analysis periods, ramp metering significantly improved traffic operations during the morning peak. Traffic conditions remained the same during the afternoon peak period. Table 4.17 summarizes the statistical analysis.

Table 4.17: Hypothesis Testing at I-35 N @ Johnson Dr.

Sample	N	Mean	StDev	SE Mean	T-value	DF	P-value
AM Flow Before	9	5653	682	227			
AM Flow After	9	5085	755	252	1.676	16	0.057
PM Flow Before	12	5280	486	140			
PM Flow After	12	5064	518	150	1.052	22	0.152
AM Speed Before	9	51.22	7.34	2.50			
AM Speed After	9	65.71	1.02	0.34	-5.831	16	<0.001*
PM Speed Before	12	55.17	3.81	1.10			
PM Speed After	12	53.99	6.90	2.00	0.521	22	0.304

* Statistically significant at 95% confidence level

Chapter 5: Conclusions and Recommendations

This research project conducted a “before” and “after” evaluation of ramp metering along an I-35 corridor in the Kansas City area to consider safety and traffic impacts of ramp meters in specific locations. The “before” analysis period was August to December 2015, while the “after” analysis period was October 2021 to February 2022 to allow for final ramp meter location selection, construction, initial ramp meter implementation, and COVID-19-related delays. The analysis focused on six merge junctions with ramp meters: four along I-35 S and two along I-35 N. Crashes that occurred within a 1-mile radius from each merge during the analysis intervals (morning and afternoon peak periods) were further analyzed. Analysis results revealed significant safety benefits at all locations, with crash frequency decreasing 54.8%–83.3%, except for the I-35 N @ 7th St. Trfy. location, where the number of crashes did not change (0% reduction), which corresponded to only one crash event. The crash frequency was normalized for exposure, and the resulting crash rates decreased significantly (13%–82.5%, with an average of 56.4%) after the deployment of ramp metering at most locations. However, at the I-35 N @ 7th St. Trfy. location, the crash rate increased 5.8% due to reduced traffic.

Ramp meters also demonstrated significant operational benefits. Results showed that average travel speeds significantly improved at sites that previously experienced recurring congestion, such that traffic conditions became uncongested, resulting in significant benefits for motorists. This pattern was observed at I-35 S @ 7th St. Trfy., I-35 @ 18th St. Expy., I-35 @ 67th St., and I-35 N @ Johnson Dr. However, roadway widening south of I-35 @ 67th St. could have also contributed to improved operations. At the most congested junction, I-35 S @ Southwest Blvd., ramp metering significantly increased travel speeds, although congestion still persisted.

In addition to ramp metering, improvements in average speeds could also be attributed to lower demand since traffic levels have still not returned to pre-COVID-19 levels. However, in many cases, the observed flow rate differences were not statistically significant; therefore, the associated speed benefits could be entirely due to ramp metering. At locations with a combination of statistically significant flow rate reduction and speed increases, the operational benefits could be due to ramp meters or decreased demand or both.

The ramp metering algorithm should continue to be implemented at locations where safety and/or operational benefits were observed. However, KDOT and KC Scout should evaluate whether ramp metering is necessary at the I-35 N @ 7th St. Trfy. location since no safety or operational benefits were observed at that location.

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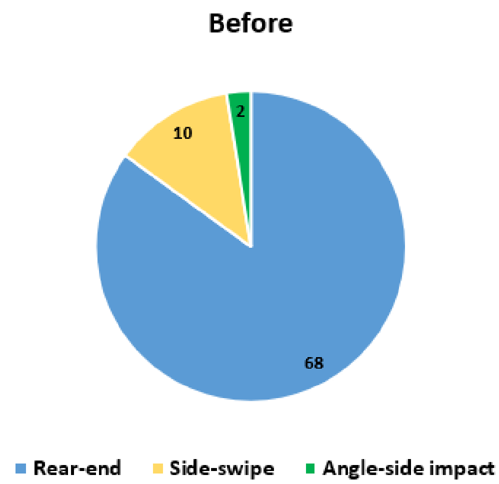
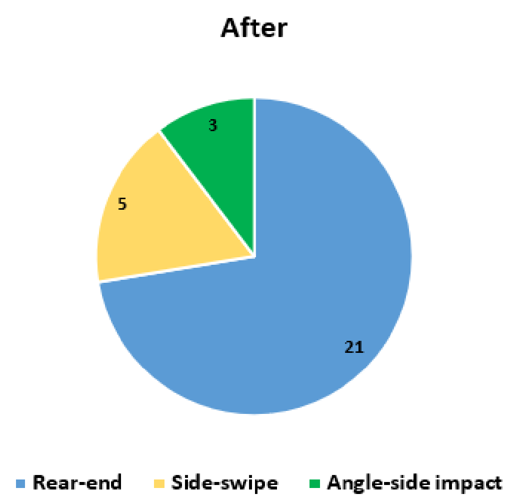
Appendix

A.1 Safety Analysis Graphs



(a)



(b)

Figure A.1: Crash Frequency Analysis Pie Chart

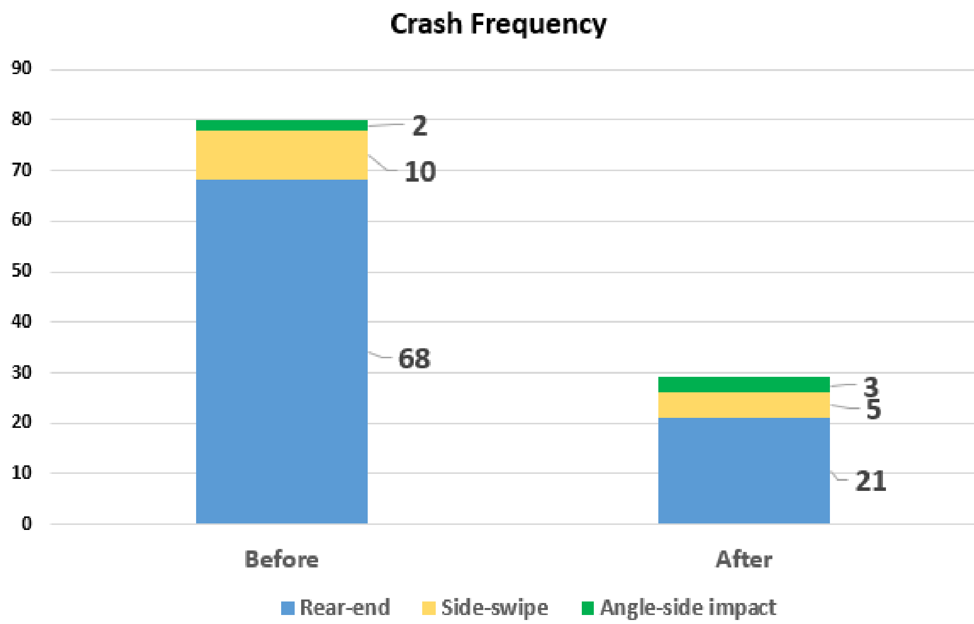


Figure A.2: Crash Frequency Analysis Bar Chart

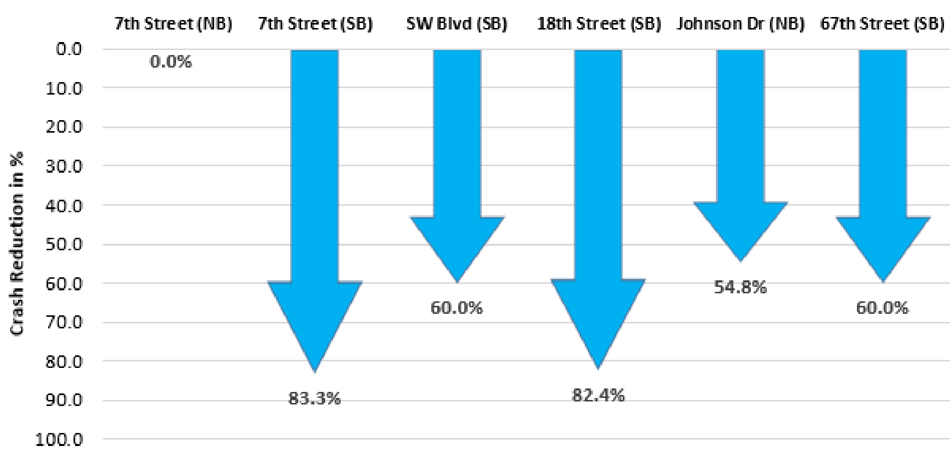


Figure A.3: Crash Reduction Percentages by Location

A.2 Traffic Operations Analysis Graphs

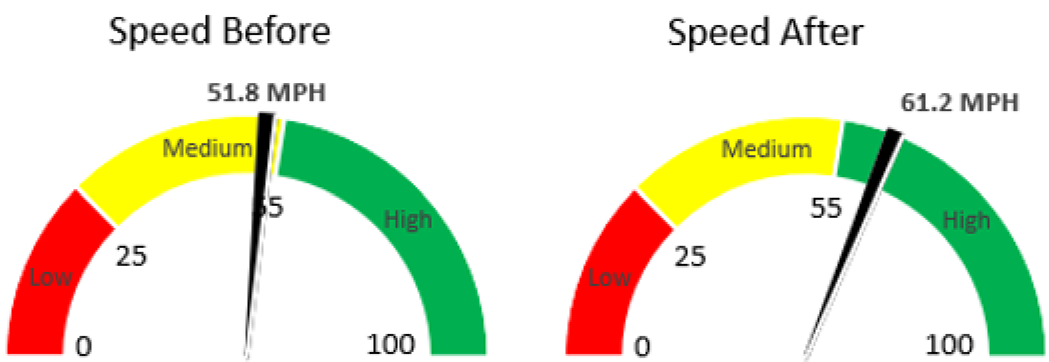


Figure A.4: Speed Improvement at I-35 S @ 7th St. Trfy. (PM Peak)

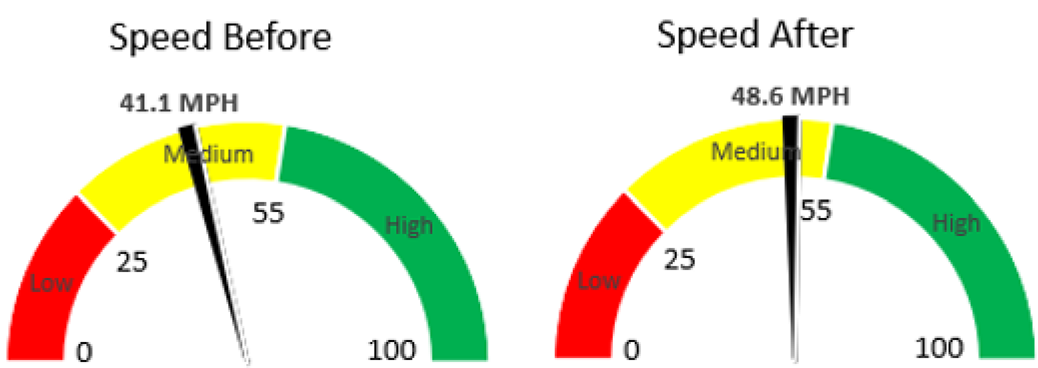


Figure A.5: Speed Improvement at I-35 S @ Southwest Blvd. (Upstream) (PM Peak)

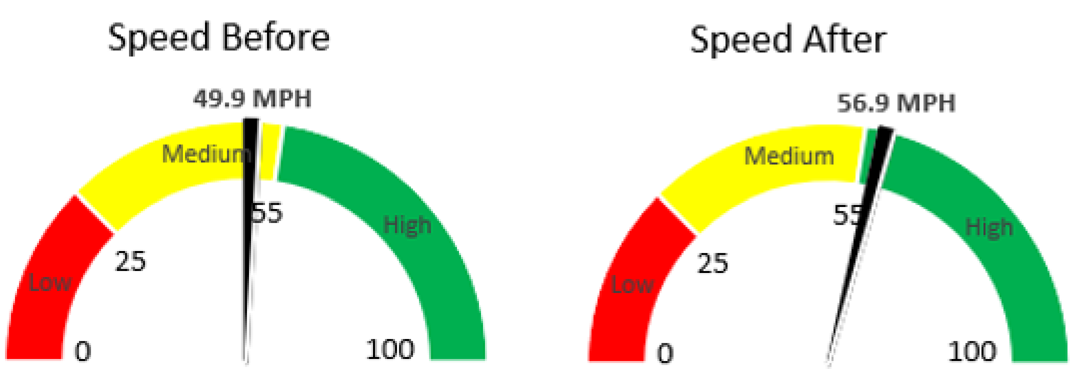


Figure A.6: Speed Improvement at I-35 S @ Southwest Blvd. (Downstream) (PM Peak)

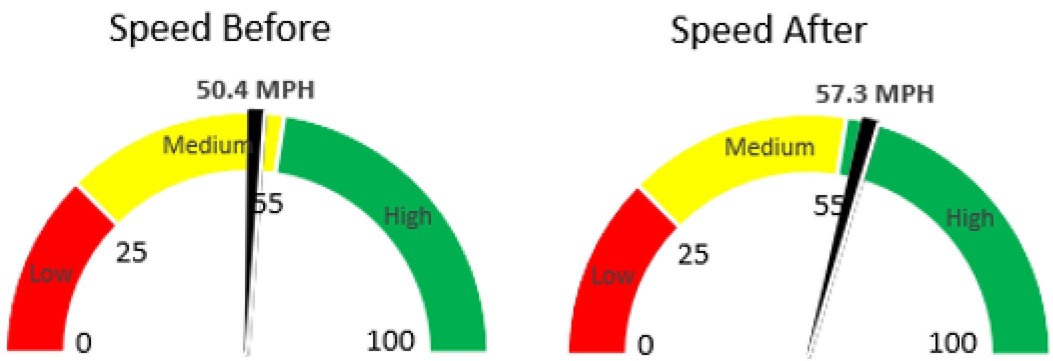


Figure A.7: Speed Improvement at I-35 S @ 18th St. Expy. (PM Peak)

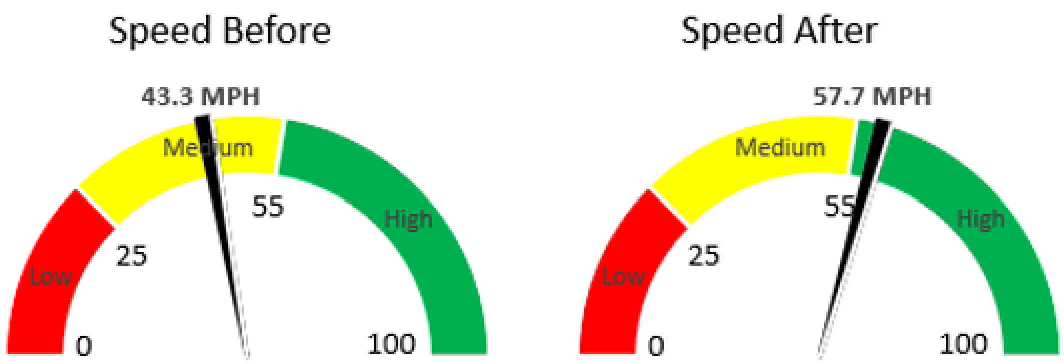


Figure A.8: Speed Improvement at I-35 S @ 67th St. (AM Peak)

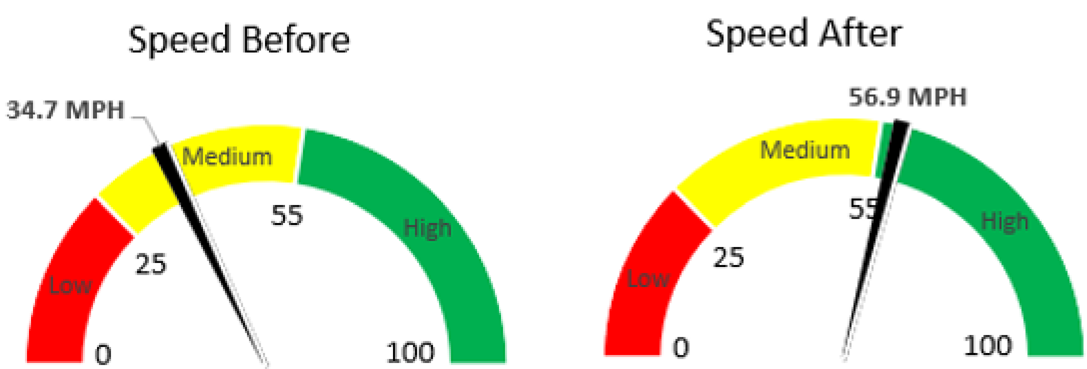


Figure A.9: Speed Improvement at I-35 S @ 67th St. (PM Peak)

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