Final Report

Pima County Speed Management Evaluation and Strategic Development: Data Driven Enforcement

Prepared for

Pima County Department of Transportation

By

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16. ABSTRACT Speed management strategies are proactive approaches to impose the speed limit and reduce crash rates. Speed feedback sign and law enforcement are generally used as one of the means of speed management strategies. Speed Feedback Signs (SFS) are usually used as a passive information device, providing speed feedback to the passing vehicles. SFS are generally installed in work zones, school zones and on rural roads, and have been shown to reduce the speed and increase the speed-limit compliance. This study evaluates the effect of several speed management strategies, namely: (1) speed feedback signs, (2) periodic law enforcement, and (3) speed feedback sign supported with periodic law enforcement on drivers' speeds. Nine locations in Pima County, Arizona, were studied in a before-after framework. The general effect of the speed management strategies showed that all the strategies were effective in reducing average speed and percent of drivers exceeding the speed limit. In addition, it was found that among all the enforcement strategies, the speed feedback sign supported with periodic law enforcement was the most effective one. Moreover, it was shown that by supporting the speed feedback sign with periodic law enforcement, the reduction in vehicles' average speed and percent of drivers exceeding the speed limit would last, even after passing the enforcement point.			
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EXECUTIVE SUMMARY

A considerable amount of research has demonstrated a direct relationship between speed and both crash frequency and crash severity. The risk of a fatal and severe crash will increase significantly as the vehicle speed increase. The risk of a fatal collision at 31 mph (50 km/h) is more than two times of a collision at 25 mph (40 km/h) and five times of a collision at 19 mph (30 km/h) (Rosén and Sander, 2009). With the limitation of infrastructure and growth in the population using vehicles, transportation agencies are required to develop the most effective and practical type of speed management strategy to impose the speed limit. Pima County Department of Transportation (PCDOT), as one of the leading public transportation agencies in the State of Arizona, is evaluating the effectiveness of several speed management strategies on arterials with the speeding issue. The findings of this study will further help PCDOT to implement more effective and cost-benefit speed management strategies.

This project is aimed at evaluating the effectiveness of three different speed management strategies, namely: 1) Speed Feedback Sign (SFS), 2) Periodic law enforcement (E), 3) SFS supported by periodic law enforcement (SFS+E), in reducing the average speed and speed violations. Periodic law enforcement is defined as Sheriff's Deputies randomly enforcing the speed throughout a specific period. For this study, the Pima County Sherriff's Department oversaw law enforcement. The Sheriff's Deputies were also asked to give citation or warning in case of speed violation. In order to evaluate the impact of each enforcement strategy, a cross-sectional study design was set up in Pima County, Arizona. In total, nine study sites were selected:

- Three sites with SFS
- Three sites with periodic law enforcement
- Three sites with SFS supported with periodic law enforcement

At each study site date, time, speed, length, and the number of vehicles axles were collected for a week. Data analysis was conducted for trucks and passenger cars independently and based on time of day and day of the week. The performance measures used in this study are: a) Average speed, b) 85th percentile speed, c) standard deviation of speed, d) proportion of vehicles exceeding the speed limit, and e) proportion of vehicles exceeding the speed limit by more than five mph (eight km/h).

The general effect of the speed management strategies (SFS, E, and SFS+E) showed that all the strategies were effective in reducing average speed and percent of drivers exceeding the speed limit. The results of comparing the effectiveness of speed management strategies showed that the SFS supported with periodic law enforcement is the most effective strategy. Further analysis of the data showed that by supporting the SFS with periodic law enforcement, the halo effect[1] could be eliminated. The results from comparing the behavior of trucks and passenger cars also revealed similar behavior. That is, both trucks and passenger cars tend to slow down after observing the enforcement. In addition, similar speed behavior was observed during weekdays and weekends.

The project team provided the following recommendations to PCDOT for further improving arterial safety, improving the effectiveness of the current speed management strategies implemented in the county, and optimizing the county's resources.

1- The results of data analysis for this project showed that supporting SFS with periodic law enforcement is the most effective speed management strategy. It is recommended that PCDOT support all the available SFSs with periodic law enforcement if possible.
2- For the sites with special geometric and topographic conditions, none of the speed management strategies (SFS, E, and SFS+E) are effective in reducing driver's average speed. It is recommended that PCDOT use other types of speed management strategies, such as speed regulating strip, rumble strip, bumps and humps for sites with special geometric and topographic condition.
3- In this project, pneumatic road tubes were used for collecting the vehicle's speed. Tubes are visible detectors that can affect the driver's behavior while approaching them. It is recommended that PCDOT use non-intrusive detectors, such as radar-based sensors, for temporary data collection.

[1] Drivers only abruptly decelerate their speed in the immediate vicinity of the enforcement zone, and after passing the enforcement zone, they will quickly regain their speed

4- When dealing with speeding issues, generally three Es are included: Engineering, Enforcement, and Education. It is recommended that PCDOT spend more resources on the Education element for enhancing public awareness on speeding issues.
5- During the project, the research team found out that some of the newer generations of the SFS are able to collect the vehicle's speed. It is recommended that PCDOT exchange the current traditional SFS for the newer generation.
6- Currently, large-scale third-party probe-based data is available to all local and state DOTs. Future research could focus on using real-time and historical third-party probe-based data to identify the locations prone to speeding. PCDOT could benefit significantly from this type of information to relocate the law enforcement resources and optimally use all their available capacity. In addition, it is recommended that PCDOT conduct further analysis of the third-party probe-based data to identify speeding hotspots for locating the potential SFS locations in the future.
7- Future studies could target the potential impact of speed management strategies on crash frequency and severity. The results could be further investigated to estimate and compare the return of investment (ROI) of each speed management strategy.

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Chapter 1

Introduction

1. INTRODUCTION

1.1 Project Background

A considerable amount of research has demonstrated a direct relationship between speed and both crash frequency and crash severity. The risk of a fatal and severe crash will increase significantly as the vehicle speed increase. The risk of a fatal collision at 31 mph (50 km/h) is more than two times of a collision at 25 mph (40 km/h) and five times of a collision at 19 mph (30km/h) (Rosén and Sander, 2009). With the limitation of infrastructure and growth in people using vehicles, agencies are required to develop the most effective and practical type of speed enforcement strategy to impose the speed limit. Pima County Department of Transportation (PCDOT), as one of the leading public transportation agencies in the state of Arizona, is evaluating the effectiveness of several speed management strategies in arterials with the speeding issue.

1.2 Project Objective

The primary goal of this project is to evaluate the effectiveness of three different speed management strategies, namely: 1) Speed feedback sign (SFS), 2) Periodic law enforcement (E), 3) SFS supported by periodic law enforcement (SFS+E), in reducing the average speed and speed violations. Periodic law enforcement is defined as randomly enforcing the speed throughout a specific time period. For this study, the Pima County Sherriff's Department (PCSD) oversaw law enforcement. More specifically, the main objectives of this research are as follows:

1- Examine and compare the impact of SFS and periodic law enforcement, individually and in tandem, on reducing the vehicles' average speed and increasing their speed limit compliance.
2- Evaluate the effect of supporting the SFS with periodic law enforcement in eliminating the halo effect[1] (drivers only abruptly decelerate their speed in the immediate vicinity of the enforcement zone, and after passing the enforcement zone, they will quickly regain their speed).

[1] Drivers only abruptly decelerate their speed in the immediate vicinity of the enforcement zone, and after passing the enforcement zone, they will quickly regain their speed

Chapter 2

Literature Review

2. LITERATURE REVIEW

Based on a report published in 2017 by the National Highway Traffic Safety Administration (NHTSA), almost 9,717 people were killed due to speeding. This amount accounts for approximately 26% of all traffic fatalities (NHTSA, 2017). The risk of a fatal collision at 31 mph (50 km/h) was more than two times of a collision at 25 mph (40 km/h) and five times of a collision at 19 mph (30 km/h) (Rosén and Sander, 2009). Consequently, agencies are considering more efficient and practical speed management strategies to impose the posted speed limit. Several types of speed management strategies are generally used to impose the posted speed limit, including speed feedback signs (Lee et al., 2006, Santiago-Chaparro et al., 2012b), law enforcement (Sisiopiku and Patel, 1999, Vaa, 1997), average section speed control (De Pauw et al., 2014, Retting et al., 2008), and speed enforcement cameras and radars (De Waard and Rooijers, 1994, Novoa et al., 2010, Jones and Lacey, 1997).

2.1 Speed Feedback Sign

Speed Feedback Sign (SFS), also known as dynamic speed display sign (DSDS), are roadside signs used to show drivers how fast they are moving. They typically operate using a radar and a changeable sign and can either be portable or fixed. The SFS is usually characterized in to two categories (Jeihani et al., 2012): 1) warn the drivers exceeding the posted speed limit by displaying “SLOW DOWN” or similar warning message (Garber and Srinivasan, 1998, McAvoy and Center, 2011), and 2) as a passive information device to show the speed limit and passing vehicles speed (Ullman and Rose, 2004).

SFSs are usually installed in work zones, school zones, and other areas prone to speed-related issues. However, the effectiveness of SFS has always been a controversial issue for practitioners (McAvoy and Center, 2011, Jeihani et al., 2012, Strawderman et al., 2013, Pesti and McCoy, 2001, Wrapson et al., 2006). Pesti and McCoy (2001) installed three SFSs along a 2.7-mile segment between two work zones on I-80 and collected speed data for five weeks. The mean, 85th percentile and standard deviation of vehicle speeds were used as the measures of effectiveness. Pesti and McCoy (2001) found that SFS was effective in reducing the speed and increasing the speed-limit compliances during the study period. Similar studies on a high-speed temporary work zone showed that SFS could reduce the speed in the work zone by about five mph (eight km/h) (Carlson et al., 2000). These studies show SFS is moderately effective in work zones in some instances.

Ulman and Rose (2005) installed SFS in a school zone, horizontal curve, and speed transition zone that is ahead of a school zone. The results from their study showed that SFS could reduce the speed by nine mph (14 km/h) in school zones and by less than five mph (eight km/h) in other locations. Short-term and long-term effects of SFS in the school zone were assessed in a study in South Korea (Lee et al., 2006). Two school zones were selected, and two SFS were installed. The short-term results showed that the speed of vehicles was reduced by 17.5% throughout the day. However, long-term results showed that the speed was reduced by only 12.5% throughout the day at the SFS locations (Lee et al., 2006).

The effectiveness of SFS in reducing speed on urban roads and in transition areas was also assessed in many studies. Wrapson et al. (2006) installed SFS on a congested two-lane road in Waitakere City, New Zealand. The results of the before and after study demonstrated a statistically significant reduction in the proportion of drivers exceeding the speed limit by six mph (10 km/h). In another study in London, Walter and Broughton (2011) assessed the impact of installing SFS on single-lane urban roads. This study was conducted at ten sites in London for one to three weeks. Overall, the average vehicle speeds for all sites were reduced by 1.4 mph (2.3 km/h). In addition, a statistically significant increase in speed limit compliance was achieved. Cruzado and Donnell (2009) also evaluated the impact of SFS on transition areas. In this study, twelve sites were selected such that each had a different speed limit transition. An SFS was active for a one- to two-week period at each site. The results showed that the average vehicle speed was reduced by six mph (10 km/h), and the number of vehicles exceeding the speed limit was also reduced. However, the observed reduction was no longer seen after removing the signs.

Another study investigated the impact of installing SFS on rural roads. SFSs were installed on State Highway 164, a two-way rural highway in Wisconsin. Vehicle data was collected over an area extending 1,125 ft (343 m) upstream and 900 ft (274 m) downstream of the SFS. The results of speed monitoring showed that the average vehicle speed was significantly reduced 1,200 ft (366 m) to 1,400 ft (427 m) upstream of the SFS. However, downstream of the SFS, speeds started to increase 300 ft (91 m) to 500 ft (152 m) past the SFS (Santiago-Chaparro et al., 2012a). The findings indicate the SFS are only effective at the sign location and not applicable for influencing the speed in other locations.

2.2 Periodic Law Enforcement

Onsite law enforcement is another common strategy effective in reducing the operating speed and increasing the speed limit compliance (Stanojević et al., 2018, Holland and Conner, 1996). Elliott and Broughton (2005) found that using periodic physical law enforcement can reduce the average speed by two to three mph. Walter and Broughton (2011) studied the impact of increased law enforcement on a route in south London and found out that increasing law enforcement reduced the average speed and vehicles going with extremely high speed along the route. Newstead et al. (2004) studied the effect of increase in law enforcement in Queensland, Australia, through a program called Road Safety Initiatives Package (RSIP). The authors found that implementing the RSIP program can reduce a large portion of vehicles exceeding the speed limit in a 37 mph (60 km/h) zone. In addition, it was shown that the effectiveness of periodic or random physical law enforcement will last up to 1.5 miles (2.4 km) to 5 miles (8 km) downstream of the enforcement sites (Newstead et al., 2004, Elliott and Broughton, 2005), much longer than other fixed speed management strategies.

2.3 Average Section Speed Control and Camera Enforcement

Average section speed control and camera enforcement are another type of speed enforcement that are deployed widely in different states. The advantage of automated section speed control is that the average speed of vehicles over a section will be recorded (De Pauw et al., 2014). The major drawback of average speed control or camera enforcement is that implementing cameras is not legal in many states, including Arizona.

De Pauw et al. (2014) evaluated the effectiveness of automated section speed control on a three-lane motorway with a speed limit of 75 mph (120 km/h) in Flanders, Belgium through a before-and-after study. The results of this study showed a significant reduction of 3.63 mph (5.84 km/h) in average speed in the controlled segments. In addition, the odds of drivers exceeding the speed limit and speed limit by 10% was reduced by 74% and 86%, respectively. Retting et al. (2008) also evaluated the effectiveness of the automated speed enforcement program implemented in Montgomery County, Maryland. The authors collected vehicle speeds for six months before and after implementing the automated speed enforcement. The results of their study showed that this enforcement is effective in reducing the percent of vehicles going over the speed limit. In addition, the results of public opinion surveys showed that the majority of drivers supported automated speed enforcement.

The indirect impact of deploying average Section Speed Control has been studied in a Motorway A1 Milan–Naples, Italy. Montella et al. (2012) evaluated the safety effectiveness of the automated section speed enforcement system. The results of their study showed that deploying the automated section system is effective in reducing the fatal crash, severe, and non-severe crash by 31.2 %, 55.6%, and 26.6 %, respectively. The effectiveness of deploying average speed control on a motorway in Austria was evaluated by Stefen and Winkelbauer (2006). They estimated that after deploying average speed control, the fatal crash and injury crashes are reduced by 33.3% and 48.8%, respectively.

2.4 Lessons learned

This section introduced the highlights of three types of speed management strategies, namely: 1) SFS, 2) law enforcement, and 3) average section enforcement using speed cameras. Based on the evaluation results of the previous studies, all these strategies are effective in reducing vehicles' average speed and increasing speed limit compliance. However, each of these strategies has its drawbacks. SFS and speed cameras suffer from the halo effect. That is, the vehicles only slowdown in the vicinity of the sign or speed camera and will regain their speed after passing the sign. Moreover, law enforcement is very costly, and some jurisdictions might have limited enforcement resources. Last but not least, due to the restriction of using cameras in some states, section control with speed cameras is not legally allowed to be implemented in some states. Therefore, in this project, the research team, with support from PCDOT evaluates a new strategy, supporting SFS with periodic law enforcement (SFS+E) to make the most of the available technologies and resources. SFS+E is aimed to circumvent the halo effect of SFS by supporting it with law enforcement. Additionally, the proposed method might be more cost-beneficial because enforcement is only conducted periodically and might be able to save more resources.

To evaluate and compare the effectiveness of SFS+E with more conventional strategies such as SFS-only and law enforcement-only, a cross-sectional study design was set up in nine study sites in Pima County, Arizona: three sites with SFS, three sites with periodic law enforcement, and three sites with SFS supported with periodic law enforcement (SFS+E). In the next section, “Data Description,” data and the study sites used for this project will be elaborated.

Chapter 3

Data Description

3. DATA DESCRIPTION

In this section, the study sites and data collection layout will be explained. To evaluate the effectiveness of the proposed speed management strategies in reducing the average speed and speed violations, a cross-sectional study design was set up in nine study sites in Pima County, Arizona: three sites with Speed Feedback Sign (SFS), three sites with periodic law enforcement (E), and three sites with SFS supported with periodic law enforcement (SFS+E).

Periodic law enforcement is defined as randomly enforcing the speed throughout a specific period. For this study, the Pima County Sherriff Department (PCSD) oversaw law enforcement. The sheriff's deputies were asked to stay at the police pullout randomly throughout the data collection of each site. The sheriff's deputies were also asked to give citation or warning in case of speed violation. SFSs in this project are fixed black and white rectangle sign with "YOUR SPEED" text above the display. When excessive speed is detected, the "SLOW DOWN" message is displayed. Otherwise, the vehicle speed is displayed. The signs are paired with speed-limit signs for driver reference, as shown in Figure 3.1.

Figure 3.1 Speed Feedback Sign evaluated in this study

As illustrated in Figure 3.2, three pneumatic road tubes are installed at each study site. Each pneumatic road tube collects “date,” “time,” “speed,” “length,” and “number of vehicles axles” during the study period. Each tube’s function is elaborated as follows.

1) Tube #1: before the implemented speed management strategy (drivers were unaware of the speed management strategy)

2) Tube #2: in the vicinity of the implemented speed management strategy (drivers were aware of the speed management strategy before passing this tube)

3) Tube #3: after the implemented speed management strategy (drivers had enough time to regain their speed)

Pneumatic road tubes are sensors that work based on the burst air pressure change caused by vehicle's tires crossing over the tubes. The pressure pulse closes an air switch, producing and transmitting electrical signals to the control device installed on the roadside. Pneumatic road tubes are portable, and the control device uses rechargeable batteries as a power source.

In order to collect the vehicles' speed and vehicle length, at each location, a pair of pneumatic road tubes were installed. Figure 3.2 illustrates the data collection layout for our study sites. A similar layout was used for all the study sites, as shown in Figure 3.2.

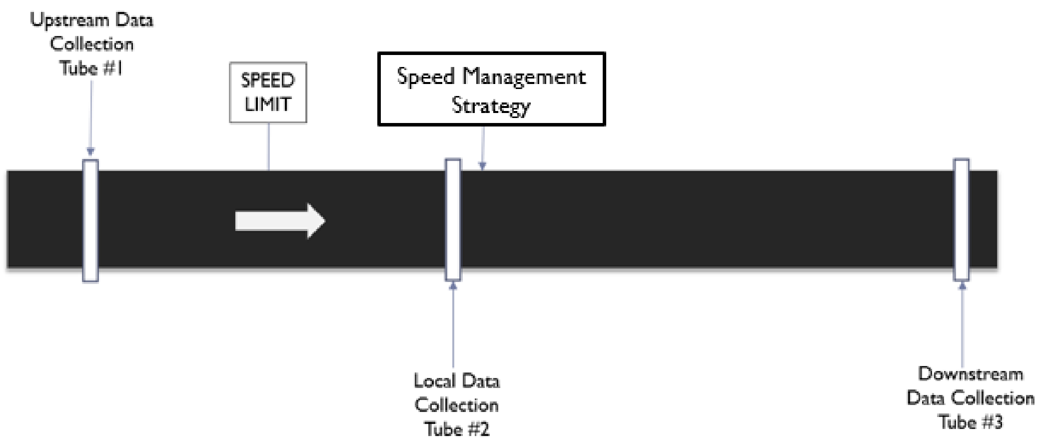


Figure 3.2 Data collection layout

Tube #1 is located in a spot that drivers passing it are not aware of any speed management strategy on the road. Tube #2 is located in the vicinity of the speed management strategy. Tube #3 is located after the speed management strategy, providing enough time (distance) for the drivers to regain their speed. Figure 3.3 illustrates some pictures taken from the data collection process.

Figure 3.3 Data collection pictures

Detailed information regarding the study sites and data collection periods are provided in Table 3.1.

PCDOT and PCSD have several restrictions for selecting the study sites:

1) The selected sites for SFS and SFS+E strategy needed to have an active SFS

2) The selected sites for E and SFS+E needed to have police pullouts in the vicinity of the SFS

3) High-risk locations were off-limits (since the sheriff's deputies were not able to monitor or enforce the speeds safely)

Considering these constraints, nine sites on arterials in Pima County were selected. A brief description of the nine selected sites is shown in Table 3.1.

Table 3.1 Study Site Description

Site ID	Locations	Speed Management Strategy*	Direction	Speed Limit (mph)	Geometric and topographic condition	Sample Size	Data Collection Period
1	W Ina Rd. @ N Leonardo Da Vinci Way	SFS+E	WB	45	Normal	221,099	March19th-March 26th 2019
2	W Ina Rd. & N @ Montebella Rd.	SFS+E	EB	45	Normal	136,890	Nov. 13th -Nov.20th 2018
3	1st Ave. @ Rudasill Rd.	SFS+E	SB	45	Downgrade	208,550	Feb.25th -March 5th 2019
4	W Irvington Rd. @ S Mission Rd.	SFS	SB	45	Normal	217,792	April 8th-April 15th 2019
5	W River Rd. @ N La Cañada Dr.	SFS	WB	45	Normal	239,554	April 30th- May 7th 2019
6	S Houghton Rd. @ E Bekke Rd.	SFS	SB	50	Curvature and side street entrance in the vicinity of Tube #1	96,677	April 9th -April 5th 2019
7	E Skyline Dr. @ E Orange Grove Rd.	E	EB	45	An intersection in the vicinity of Tube #2	161,524	Dec. 4th -Dec.11th 2018
8	E Sunrise Dr. @ Hacienda Del Sol Rd.	E	EB	45	Downgrade	178,381	Dec. 4th -Dec.11th 2018
9	E Camino Del Río @ N Sabino Canyon Rd.	E	NB	40	Normal	299,797	May 14th- May 21th 2019

* SFS+E= Speed feedback signs supported by periodic law Enforcement; SFS= Speed feedback Sign only; E=Law Enforcement only

More detailed information for each study site is provided next.

3.1 Study Sites

3.2.1 W Ina Rd. @ N Leonardo Da Vinci Way (WB)

This site is equipped with SFS supported by periodic law enforcement (SFS+E). At this location, the SFS and the police pullout were located right after N Leonardo Da Vinci Way on the eastbound of West Ina Rd. The distance between the SFS and the police pullout to the closest intersection (N Oracle Rd. and W Ina Rd.) is about 0.67 miles (1.1 km). The location of the installed tubes, the SFS, and the police pullout are demonstrated in Figure 3.4.

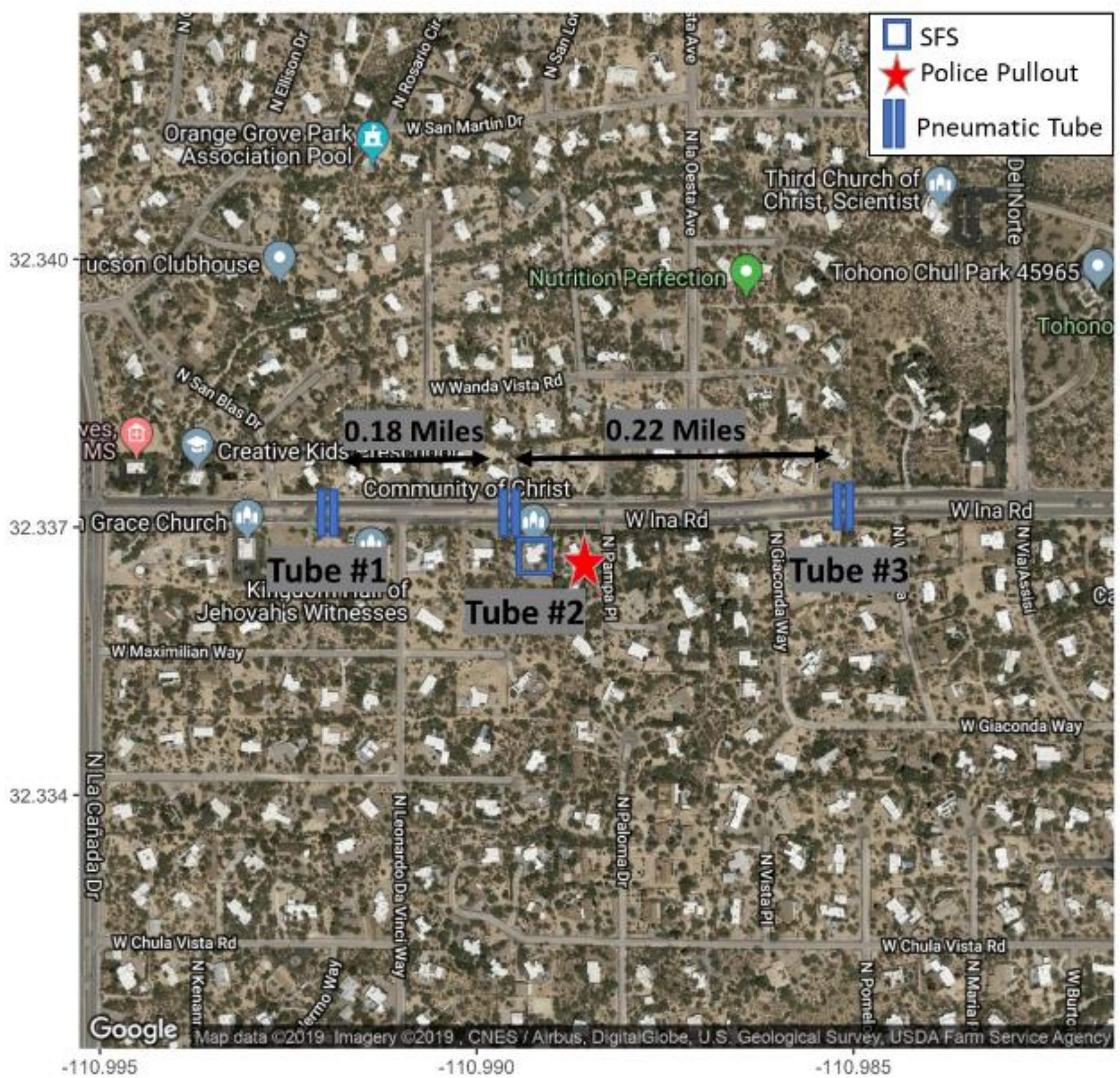


Figure 3.4 Site #1 (W Ina Rd. @ N Leonardo Da Vinci Way)

3.2.2 W Ina Rd. @ & N Montebella Rd. (EB)

This location is equipped with SFS supported by periodic law enforcement (SFS+E). At this location, the SFS and the police pullout are located right after N Montebella Rd. on the eastbound of West Ina Rd. The distance between the SFS and the police pullout from the closest intersection

(N La Canada Dr.) is about 0.5 miles (0.8 km). The location of the installed tubes, the SFS, and the police pullout are demonstrated in Figure 3.5.

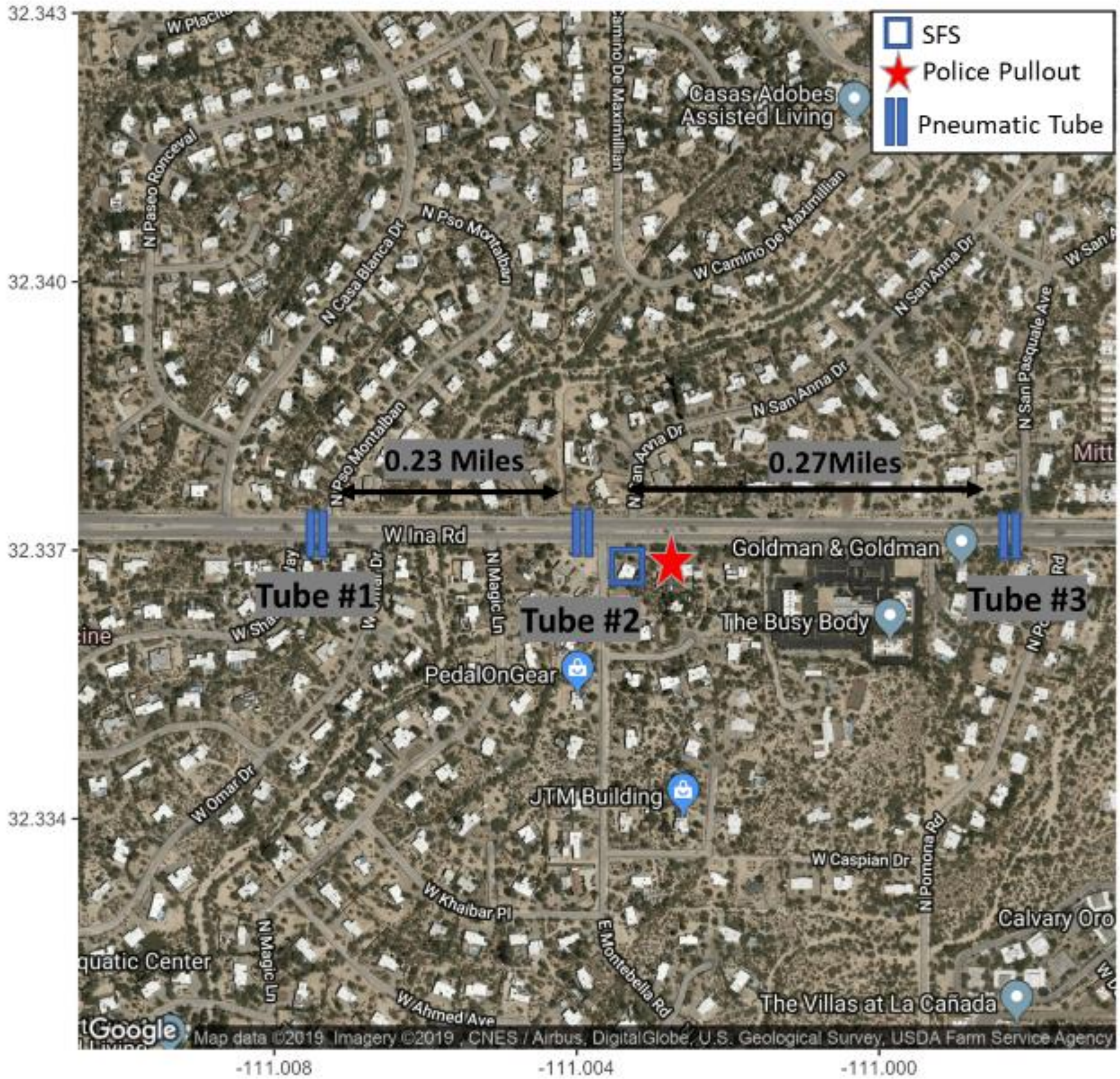


Figure 3.5 Site #2 (W Ina Rd. @ & N Montebella Rd. (EB))

3.2.3 N 1st Ave. @ Rudasill Rd. (SB)

This location is equipped with SFS supported by periodic law enforcement (SFS+E). At this location, the SFS and police pullout are located right after Rudasill Rd. on the southbound of N 1st Ave. The distance between the SFS and the police pullout to the closest intersection (N 1st Ave. and River Rd.) is about 4.28 miles (6.8 km). This site is on a downgrade segment with an average grade of 3%. The location of the installed tubes, the SFS and the police pullout are demonstrated in Figure 3.6.

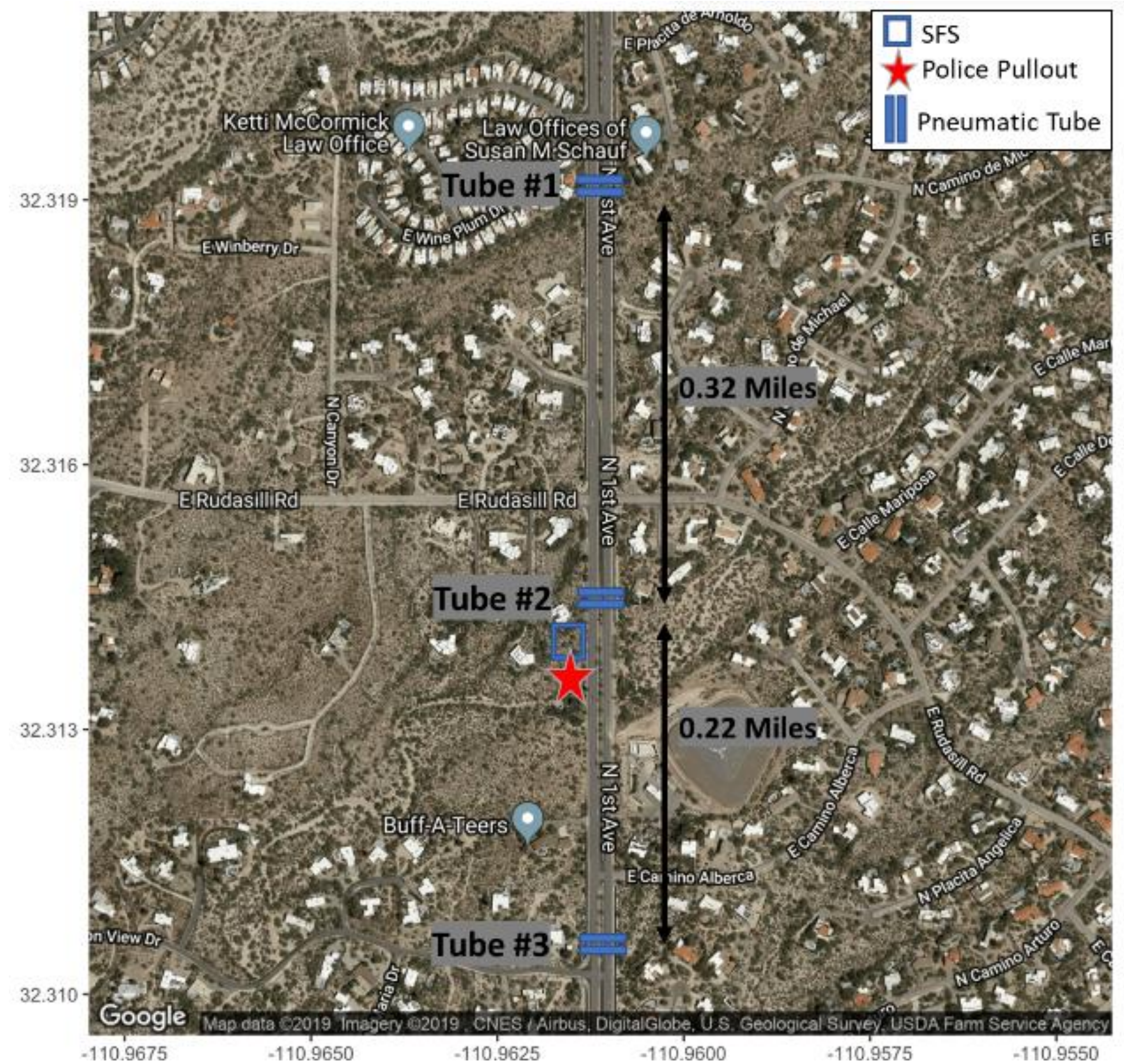


Figure 3.6 Site #3 (N 1st Ave @ Rudasill (SB))

3.2.4 W Irvington Rd. @ S Mission Rd (NB)

This site is enforced with only SFS. The SFS is located on the W Irvington Rd. The distance between the SFS to the closest intersection (N Irvington Rd. and S Mission Rd.) is about 0.24 mile (0.4 km). The location of the installed tubes and the SFS are demonstrated in Figure 3.7.

Figure 3.7 Site #4 (W Irvington Rd. @ S Mission Rd. (NB))

3.2.5 W River Rd. @ N La Cañada Dr. (WB)

This site is equipped with only SFS. The SFS is located on the W River Rd. after N La Cañada Dr. The distance from the SFS to the closest intersection is 0.56 mile (0.9 km). The location of the installed tubes and the SFS are demonstrated in Figure 3.8.

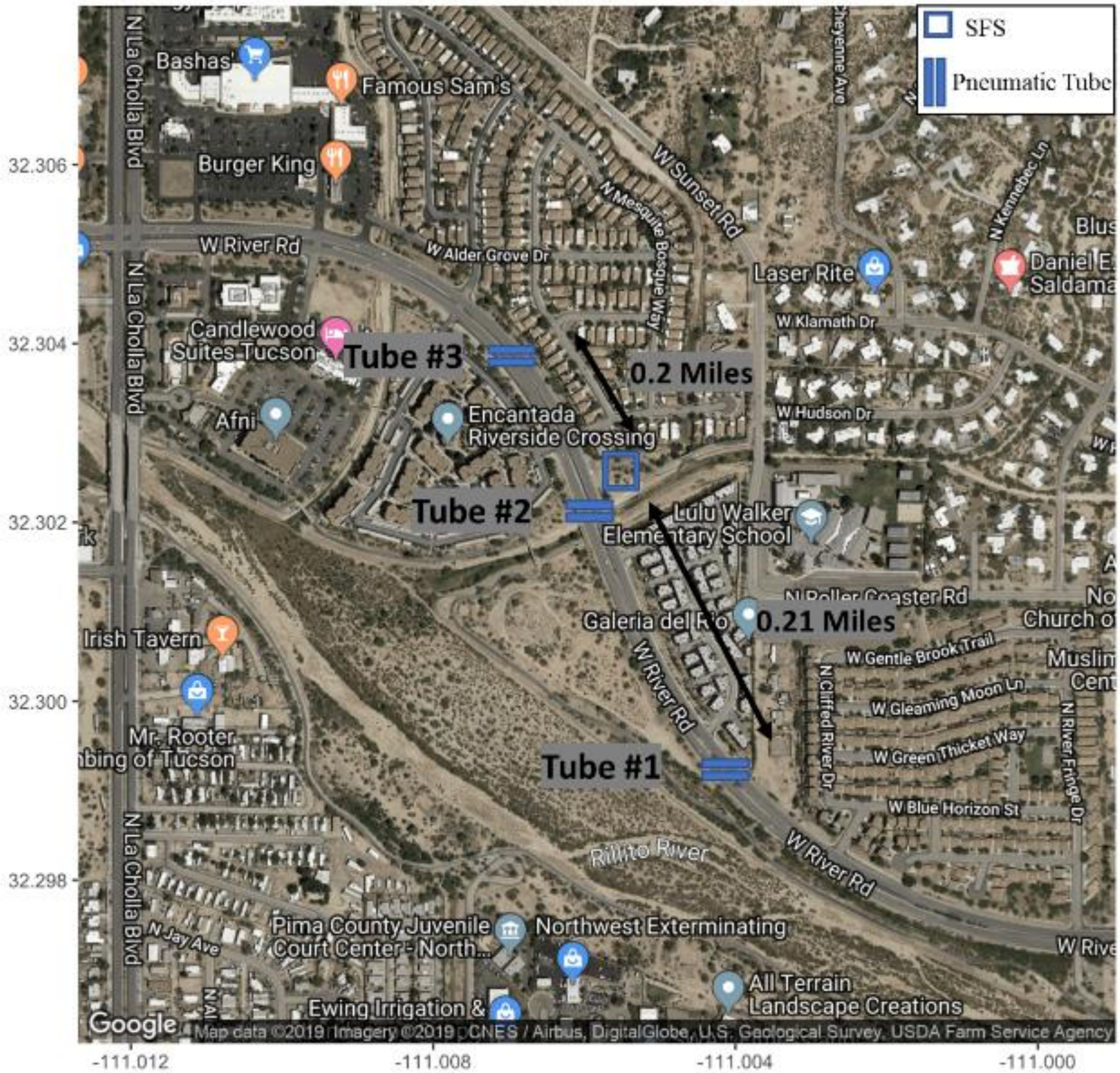


Figure 3.8 Site #5 (W River Rd. @ N La Cañada Dr. (WB))

3.2.6 S Houghton Rd. @ E Bekke Rd. (SB)

This site is equipped with only SFS. The SFS is located on the southbound of S Houghton Rd. The location of the installed tubes and the SFS are demonstrated in Figure 3.9. It is worth to mention that Tube #2 is located right after a side street; the vehicles entering from this side street will significantly impact the data collected at Tube #2.

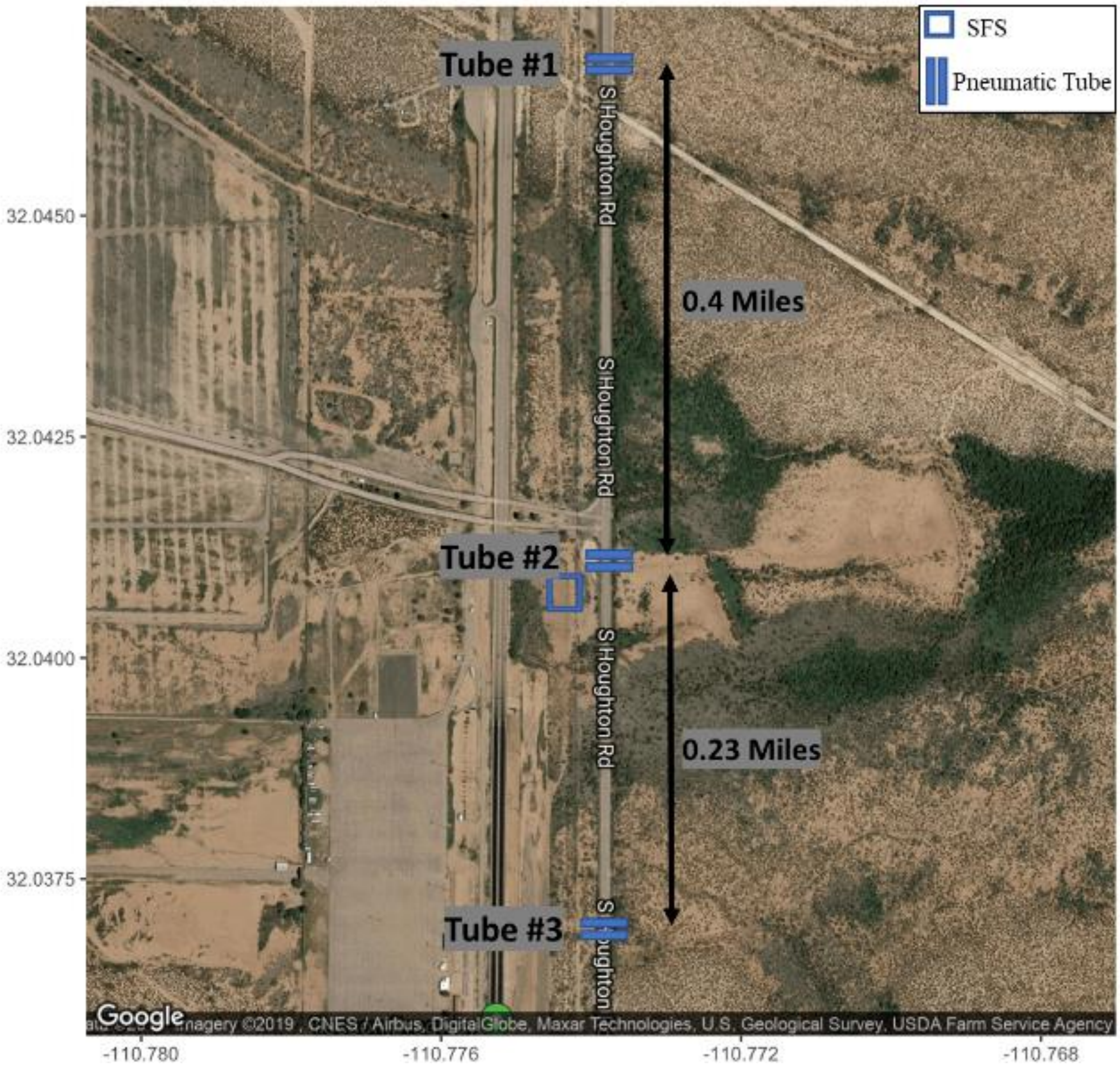


Figure 3.9 Site #6 (Houghton Rd. @ E Bekke Rd. (SB))

3.2.7 E Skyline Dr. @ E Orange Grove Rd. (EB)

This site is enforced with periodic law enforcement. The police pullout is on the eastbound of E Orange Grove Rd. It is worth to mention that Tube #2 is located right after the intersection. Therefore, the vehicles hitting the red light will significantly impact the data collected at this point. The location of the installed tubes and the police pullout are demonstrated in Figure 3.10.

Figure 3.10 Site #7 (E Skyline Dr. @ E Orange Grove Rd. (EB))

3.2.8 E Sunrise Dr @ Hacienda Del Sol Rd (NB)

This site is enforced with periodic law enforcement. The police pullout is on the northbound of E Sunrise Dr. This location is a downgrade segment with an average grade of 3%. The location of the installed tubes and the police pullout are demonstrated in Figure 3.11.

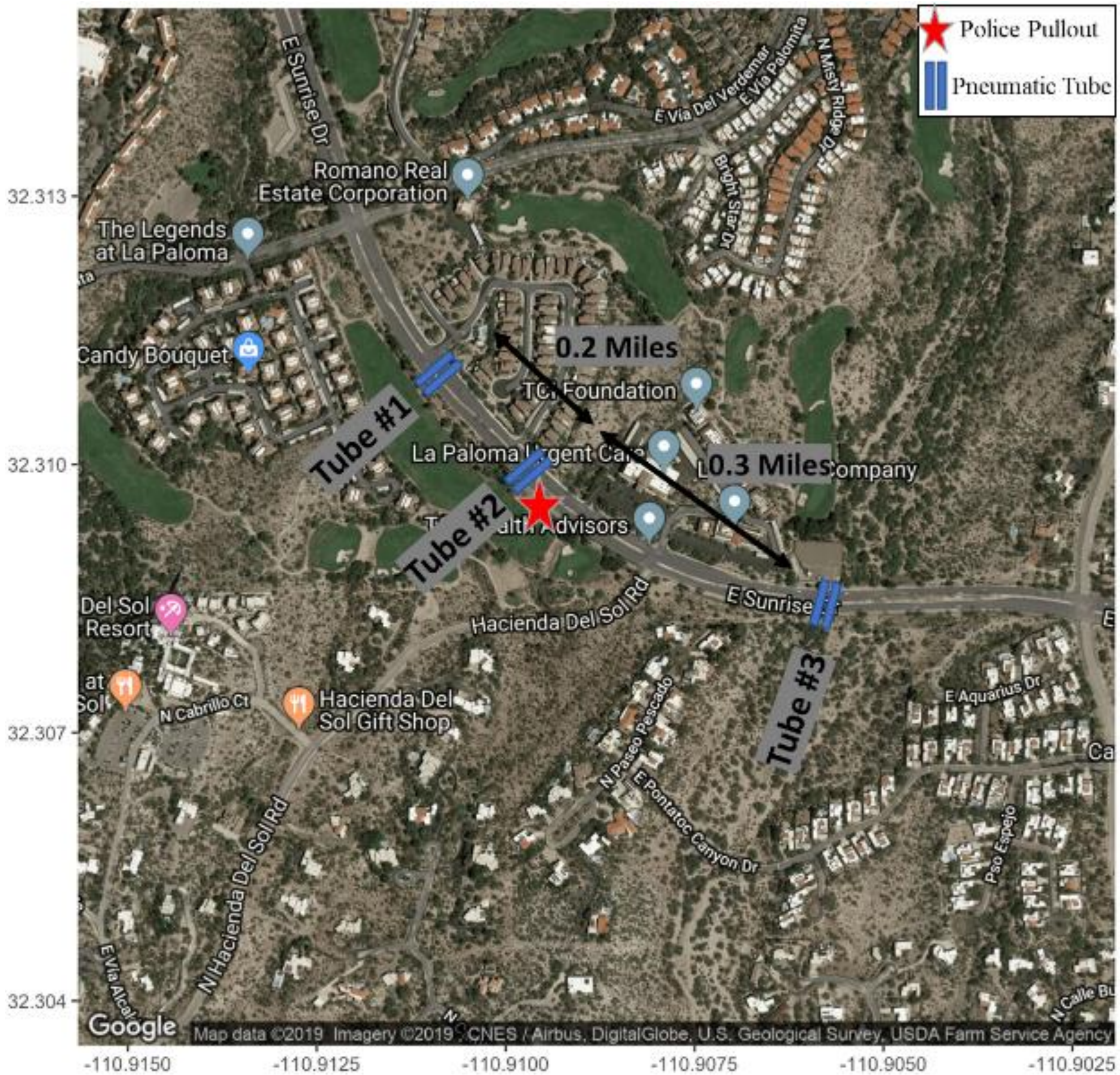


Figure 3.11 Site #8 (E Sunrise Dr. @ Hacienda Del Sol Rd. (NB))

3.2.9 E Camino Del Río @ N Sabino Canyon Rd. (NB)

This site is enforced with periodic law enforcement. The location of the installed tubes and the police pullout are demonstrated in Figure 3.12. It is worth to mention that Tube #1 is installed right after a major side street; the vehicles entering from this side street will significantly impact the data collected at Tube #2.

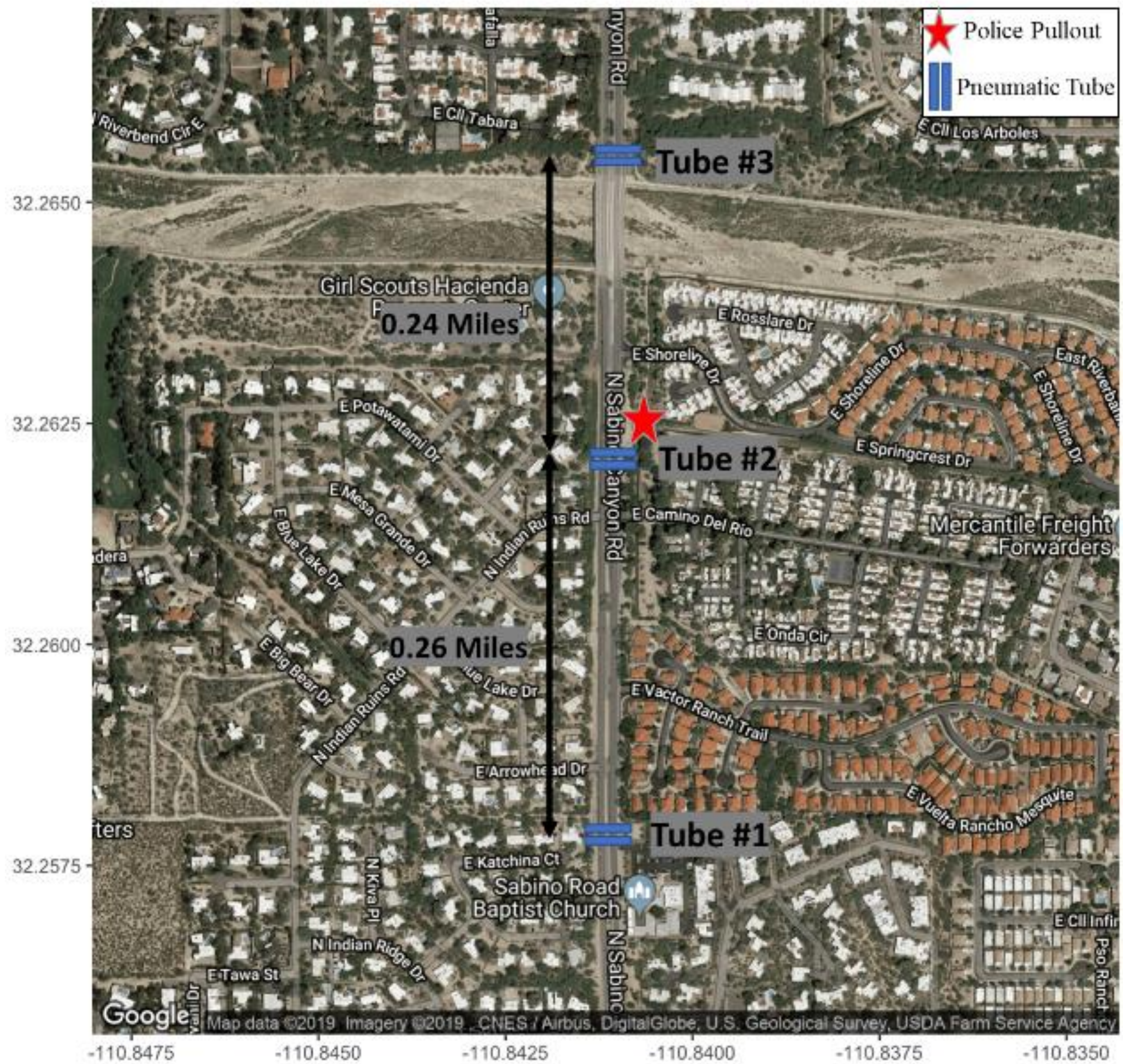


Figure 3.12 Site #9 (E Camino Del Río @ N Sabino Canyon Rd. (NB))

It is worth to mention that several of the study sites described above (Sites # 3, 6, 7, and 8) have specific geometric and topographic conditions. Sites #3 and 8 are on a downgrade segment, Tube #2 in Site #7 is in the vicinity of an intersection, and Site #6 is in a sharp curvature. These specifications are carefully studied and addressed in this project. In the following chapter, the results of data analysis for each site will be described thoroughly.

Chapter 4

Results

4. RESULTS

4.1 Spatial and Temporal Analysis

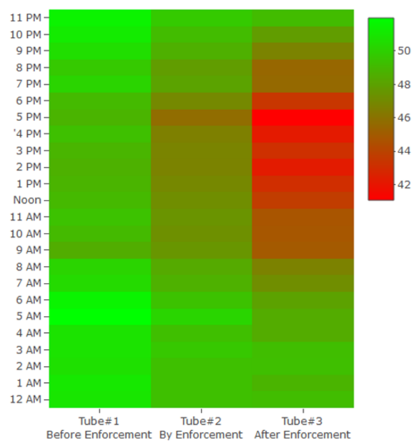
The data collected from each study site is stored in a SQL database. Each database includes a large amount of information about the date, time, speed, length of vehicles, and the number of vehicles' axles. To better visualize the overview of the collected data, heatmaps are used in this project. A heatmap is a graphical representation of information where the individual values are represented as a color. The main goal of using a heatmap is to direct viewers towards the data points that are more important.

Figure 4.1 illustrates a speed distribution heatmap for all the study sites. In order to produce these heatmaps, the speed data is aggregated into a one-hour duration. The green color indicates higher speeds, and the red color indicates lower speeds. For each heatmap, three separated columns represent the average speed at each tube (Tube #1, #2 and #3).

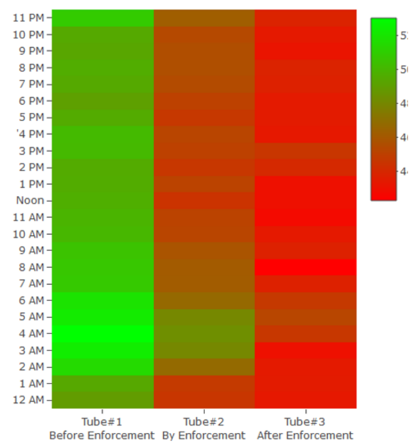
In general, at nighttime (from midnight to 6 am), in almost all the study sites, the vehicles are operating at a higher speed compared to other times of the day. In most of the study sites, the vehicles slowdown in the vicinity of the speed management strategy zone and regain their speed after passing this zone.

At Sites #1 and #2 during all the time of day, the average speed decreased moving from Tube #1 to Tube #2. These two sites are equipped with Speed feedback sign (SFS) supported by periodic law enforcement. At Sites #3, #6 and #8 for almost all times of day, the average speed is increasing moving from Tube #1 to Tube #3. This can be explained because of the topographic condition of these three sites (Sites #3 and #8 are downgrade, and there is a side street close to Tube #1 at Site #6. At Sites #4, #5, #7, and #9 vehicles average speed reduced going from tube #1 to tube #2, and then it will increase going from Tube # 2 to Tube #3. Sites #4 and #5 are only equipped with SFS, and Sites #7 and #9 are only enforced with periodic law enforcement.

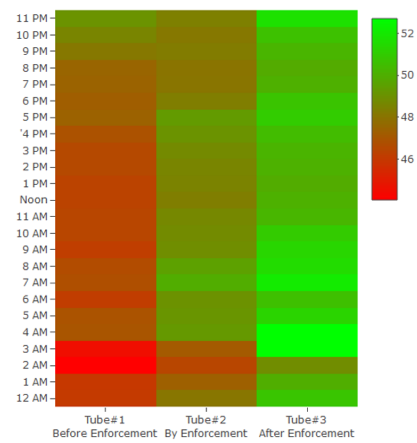
Site #1: W Ina Rd. @ N Leonardo Da Vinci Way



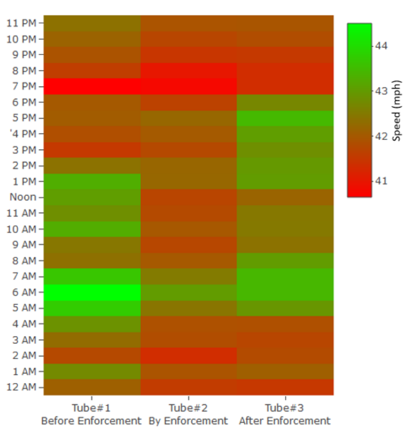
Site #2: W Ina Rd. & N @ Montebella Rd.



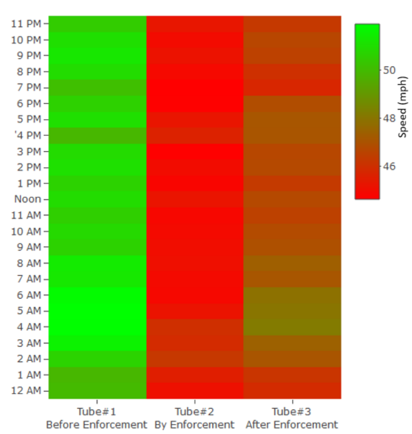
Site #3: 1st @ Rudasill Rd.



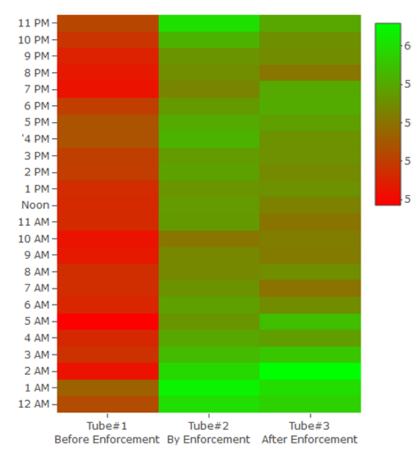
Site #4: W Irvington Rd @ S Mission Rd.



Site #5: W River Rd @ N La Cañada Dr.



Site #6: S Houghton Rd. @ E Bekke Rd.



Site #7: E Skyline Dr @ E Orange Grove Rd

Site #8: E Sunrise Dr @ Hacienda Del Sol Rd

Site #9: E Camino Del Río @ N Sabino Canyon Rd

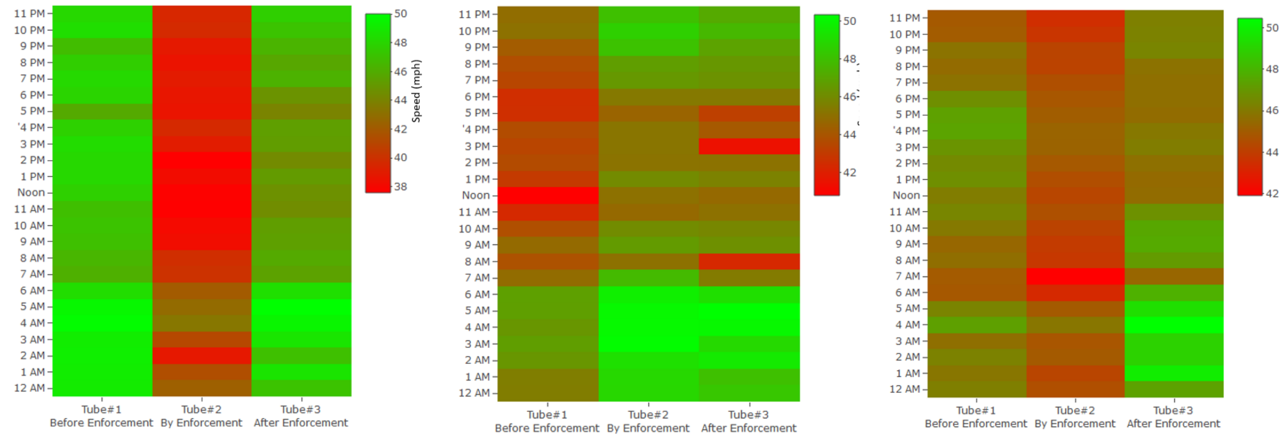


Figure 4.1 Speed heat maps based on the hour of the day

4.2 Data Analysis

The performance measures used for evaluating the speed management strategies are: average speed, 85th percentile speed, the standard deviation of speed, the proportion of vehicles exceeding the speed limit, and the proportion of vehicles exceeding the speed limit by more than five mph (eight km/h). In addition, the data is broken down based on the following temporal classification for trucks and passenger cars separately:

- Day (6 am to 10 pm), peak-hours (6 am to 9 am and 4 pm to 6 pm), and off-peak hours (9 am to 4 pm and 6 pm to 10 pm)
- Weekday (Monday to Friday) vs. weekend (Saturday and Sunday)

Tables 4.1 and 4.2 present the average speed, 85th percentile speed, standard deviation of speed, proportion of vehicles exceeding the speed limit, and proportion of vehicles exceeding the speed limit by more than five mph for passenger cars and trucks at each site, respectively. The results are separated based on time of day (peak and off-peak) and day of the week (weekend and weekday).

In Tables 4.1 and 4.2, the immediate speed effect is the vehicle average speed difference between Tube #2 and Tube # 1. The positive values indicate that the drivers sped up after entering the speed management strategy zone, and negative values indicate that they slowed down after entering this zone. The secondary effect shows the vehicle speed difference between Tube #3 and Tube # 2. Similarly, the positive values indicate that the drivers sped up after passing the speed management strategy zone, and the negative values indicate that the drivers slowed down after passing the speed management strategy zone. In cases where the speed change is statistically significant at the level of 0.05, the values are underlined.

It can be found that generally, at Sites #1, #2, #4, #5, and #9, the implemented speed management strategies were effective in reducing the average speed. The immediate effect of speed management strategies was statistically significant at the level of p=0.05 for all these sites. Although the speed range is different during weekdays and weekends, drivers' speeding behaviors at the speed management strategy zone followed a similar trend. Comparing the general trend for trucks and passenger cars (Tables 4.1 and 4.2), for the majority of the traffic conditions, time of day and time of the week, the passenger vehicles and trucks show similar trends while observing either of the speed management strategies.

At Sites #3 and #8, the roadway has a downgrade with an average grade of 3% and 3.3 %. The results of the average speed and 85th percentile of the speed showed drivers sped up (likely due to the downgrade). In addition, the percent of vehicles going over the speed limit and going five mph over the speed limit is also increased for these sites.

At Site #6, Tube #1 was located right after the spiral of the curve and a side street entrance. Due to these two conditions, the average speed at Tube #1 could have dropped significantly. The results of average speed and 85^{th} percentile speed shows speeds increased at Tube #2, where the road was straight. In addition, the proportions of vehicles going over the speed limit and going five mph over the speed limit also increased for vehicles going from Tube #1 to Tube #3. Therefore, no conclusion for the potential impact of speed enforcement for this location could be made either.

At Site #7, the second data collection point (Tube #2) was located right after an intersection. In order to remove the impact of intersection delay on the vehicles' speed, only the vehicles with speed higher than 40 mph (64 km/h) were included in the analysis. The results show that vehicles slowed down right after observing speed enforcement. The speed reduction was statistically significant at the 5% significance level. However, it is difficult to say if the signal or the reduction strategies were the reason for the observed differences.

It is worthwhile to mention that, at Sites #2, #7, and #8, the tubes were disconnected during the weekend of data collection, and the technicians were not alerted until the next business day. Therefore, missing data was an issue for some of the sites during the weekend. Since the results for the sites with specific geometric and topographic conditions were inconclusive, for the rest of this report we focused on the sites with no specific geometric conditions - Sites #1, #2, #4, #5, #7, and #9.

Table 4.1 Performance Comparison for Different Sites-Passenger Cars

Passenger Cars			Peak Hour					Off-Peak Hour					Weekend Day				
Site	Speed Management Strategy	Measures	Tube #1 (Before enforcement)	Tube #2 (Before enforcement)	Tube #3 (After enforcement)	Immediate Effect (mph)	Secondary Effect (mph)	Tube #1 (Before enforcement)	Tube #2 (Before enforcement)	Tube #3 (After enforcement)	Immediate Effect (mph)	Secondary Effect (mph)	Tube #1 (Before enforcement)	Tube #2 (Before enforcement)	Tube #3 (After enforcement)	Immediate Effect (mph)	Secondary Effect (mph)
		Average Speed (mph)	47.5	47.2	42.7	-0.30	-4.50	47.3	47.3	44.3	0.0	-3.0	47.7	45	45	-2.7	0
		85th Percentile of Speed (mph)	51.8	51.6	50	-0.20	-1.60	51.6	51.5	50	-0.1	-1.5	52.1	52	50.6	-0.1	-1.4
1	SFS+E	Standard Deviation of Speed (mph)	4.4	4.6	6.4	-	-	4.5	4.3	5.9	-	-	4.5	4.3	5.8	-	-
		% Going Over Speed (%)	73.2	72.2	45.7	-	-	72.5	70	49.21	-	-	74.4	72	53.7	-	-
		% Going 5mph Over Speed (%)	27.9	26.3	15.3	-	-	26.7	26.1	15.46	-	-	30	31.8	18.4	-	-
		Average Speed (mph)	48.4	45.9	43.3	-2.50	-2.60	47.8	45.4	43.3	-2.4	-2.1	-	-	-	-	-
		85th Percentile of Speed (mph)	53	50.3	48.2	-2.70	-2.10	52.2	49.6	48.1	-2.6	-1.5	-	-	-	-	-
2	SFS+E	Standard Deviation of Speed (mph)	4.8	4.4	4.8	-	-	4.7	4.1	4.6	-	-	-	-	-	-	-
		% Going Over Speed (%)	77.6	55.2	33.14	-	-	74.8	51	35.2	-	-	-	-	-	-	-
		% Going 5mph Over Speed (%)	34.2	15.2	7	-	-	29.9	12.7	7.8	-	-	-	-	-	-	-
		Average Speed (mph)	46.8	49.2	50.7	2.40	1.50	46.7	48.5	49.9	1.8	1.4	46.3	49.1	41.1	2.8	-8
		85th Percentile of Speed (mph)	50.8	53.2	41.1	2.40	-12.10	50.9	52.4	54.1	1.5	1.7	50.5	52.9	54.3	2.4	1.4
3	SFS+E	Standard Deviation of Speed (mph)	4.3	4.1	4.7	-	-	4.7	4.1	4.6	-	-	4.3	4.2	4.6	-	-
		% Going Over Speed (%)	67.2	87.4	92.8	-	-	65.2	82.7	90.3	-	-	74.4	88.2	91.9	-	-
		% Going 5mph Over Speed (%)	20.5	40.5	55.8	-	-	20.5	33.6	48.2	-	-	30	38.1	51.1	-	-
		Average Speed (mph)	43	42.1	43.2	-0.90	1.10	43.3	41.7	42.4	-1.6	0.7	43	42.1	44.2	-0.9	2.1
		85th Percentile of Speed (mph)	47.2	46.4	47.2	-0.80	0.80	47	45.8	46.4	-1.2	0.6	47.5	46.2	48.4	-1.3	2.2
4	SFS	Standard Deviation of Speed (mph)	5	4.4	4.3	-	-	4.8	4.4	4.3	-	-	4.8	4.4	4.8	-	-
		% Going Over Speed (%)	27.8	23.7	30	-	-	25.9	20	23.9	-	-	30.3	22.5	34.7	-	-
		% Going 5mph Over Speed (%)	65	3.8	6	-	-	5.63	3.3	4.6	-	-	6.9	3.8	9.5	-	-
		Average Speed (mph)	51	45.8	47.2	-5.20	1.40	50.9	45	46.5	-5.9	1.5	51.4	44.9	47.2	-6.5	2.3
		85th Percentile of Speed (mph)	55.7	49.3	50.8	-6.40	1.50	55.6	49.2	50.4	-6.4	1.2	56	49.4	51.1	-6.6	1.7
5	SFS	Standard Deviation of Speed (mph)	5.1	4.9	4.1	-	-	5	4.9	4.1	-	-	5	5.4	4.2	-	-
		% Going Over Speed (%)	91.6	54.5	72.7	-	-	91.4	51.5	66.5	-	-	92.9	53	72.8	-	-
		% Going 5mph Over Speed (%)	61.9	12.9	23.3	-	-	59.1	11.42	17.9	-	-	63.4	12.5	22.8	-	-
		Average Speed (mph)	54.1	57.6	57.4	3.50	-0.20	53.4	57.4	57	4.0	-0.4	54.1	57.4	56.8	3.3	-0.6
		85th Percentile of Speed (mph)	58.9	62.9	62.3	4.00	-0.60	58	62.3	61.8	4.3	-0.5	59.3	60	61.7	0.7	1.7
6	SFS	Standard Deviation of Speed (mph)	5.4	5.2	4.9	-	-	4.9	5.1	4.9	-	-	6	4.4	5.2	-	-
		% Going Over Speed (%)	82.4	94.6	96	-	-	78	93.9	94.7	-	-	80.5	96.1	93	-	-
		% Going 5mph Over Speed (%)	42.4	72.2	70	-	-	35.6	70.8	67.3	-	-	42.7	80.5	65.6	-	-
		Average Speed (mph)	48.4	45.6	46.8	-2.80	1.20	48.6	45.1	46.2	-3.5	1.1	-	-	-	-	-
		85th Percentile of Speed (mph)	52.5	49.5	51.1	-3.00	1.60	52.7	48.8	50.5	-3.9	1.7	-	-	-	-	-
7	E	Standard Deviation of Speed (mph)	4.4	3.8	4.3	-	-	4.1	3.8	4.1	-	-	-	-	-	-	-
		% Going Over Speed (%)	74.1	23.6	54.3	-	-	78.5	23.5	51.4	-	-	-	-	-	-	-
		% Going 5mph Over Speed (%)	30	5.8	17.9	-	-	33.6	5.8	15.6	-	-	-	-	-	-	-
		Average Speed (mph)	44.2	46.7	45.5	2.50	-1.20	43.5	46.6	45.6	3.1	-1.0	-	-	-	-	-
		85th Percentile of Speed (mph)	49.2	51.4	51.4	2.20	0.00	48.5	51.1	51	2.6	-0.1	-	-	-	-	-
8	E	Standard Deviation of Speed (mph)	5.2	4.9	6.2	-	-	5.1	4.6	5.7	-	-	-	-	-	-	-
		% Going Over Speed (%)	43.1	63.4	55.2	-	-	37.9	63	55.5	-	-	-	-	-	-	-
		% Going 5mph Over Speed (%)	4.9	23.2	22	-	-	9	21.7	20.3	-	-	-	-	-	-	-
		Average Speed (mph)	52.9	51.7	54.6	-1.20	2.90	54.4	52.8	54.1	-1.6	1.3	53.9	52.1	52.9	-1.8	0.8
		85th Percentile of Speed (mph)	56.7	54.9	59.1	-1.80	4.20	57.5	55.1	57.7	-2.4	2.6	57.2	55.5	55.4	-1.7	-0.1
9	E	Standard Deviation of Speed (mph)	5.6	2.8	4.5	-	-	6.1	2.8	4.2	-	-	5.4	2.8	3.1	-	-
		% Going Over Speed (%)	72.2	58.3	71.3	-	-	74.3	50.8	72.19	-	-	75.8	58.4	72.8	-	-
		% Going 5mph Over Speed (%)	45.6	36.8	56.5	-	-	46.5	34.5	57	-	-	53.5	35.6	59.8	-	-

Table 4.2 Performance Comparison for Different Sites-Trucks

Trucks			Weekday										Weekend				
			Peak Hour					Off-Peak Hour					Day				
Site	Speed Management Strategy	Measures	Tube #1 (Before enforcement)	Tube #2 (Before enforcement)	Tube #3 (After enforcement)	Immediate Effect (mph)	Secondary Effect (mph)	Tube #1 (Before enforcement)	Tube #2 (Before enforcement)	Tube #3 (After enforcement)	Immediate Effect (mph)	Secondary Effect (mph)	Tube #1 (Before enforcement)	Tube #2 (Before enforcement)	Tube #3 (After enforcement)	Immediate Effect (mph)	Secondary Effect (mph)
1	SFS+E	Average Speed (mph)	46.3	46.2	42.7	-0.1	-3.5	46	45.3	42.9	-0.7	-2.4	46.6	46.3	42.2	-0.3	-4.1
		85th Percentile of Speed (mph)	50.6	50.6	48.8	0	-1.8	50.3	50.1	49	-0.2	-1.1	50.9	51.4	49.8	0.5	-1.6
		Standard Deviation of Speed (mph)	4.4	4.4	6.6	-	-	4.5	4.4	6.4	-	-	4.5	4.1	5.9	-	-
		% Going Over Speed (%)	62.5	65	39.64	-	-	59.4	65.1	40	-	-	65.7	73.7	48.8	-	-
		% Going 5mph Over Speed (%)	18.3	19.2	10.5	-	-	17.18	18.7	11.12	-	-	20.9	21.7	14.6	-	-
2	SFS+E	Average Speed (mph)	47.4	44.7	41.9	-2.7	-2.8	46.9	44.2	42.3	-2.7	-1.9	-	-	-	-	-
		85th Percentile of Speed (mph)	52.1	49	46.5	-3.1	-2.5	51.4	48.3	47.1	-3.1	-1.2	-	-	-	-	-
		Standard Deviation of Speed (mph)	4.7	4.5	4.6	-	-	4.6	4.6	4.8	-	-	-	-	-	-	-
		% Going Over Speed (%)	72.5	47.5	24.2	-	-	68.1	42.2	27.9	-	-	-	-	-	-	-
		% Going 5mph Over Speed (%)	28.3	10.6	3.9	-	-	23.6	9.4	5.13	-	-	-	-	-	-	-
3	SFS+E	Average Speed (mph)	45.8	48.4	51.4	2.6	3	45.6	47.7	50.4	2.1	2.7	45.3	48.5	51.1	3.2	2.6
		85th Percentile of Speed (mph)	49.8	52.1	55.2	2.3	3.1	49.6	51.5	54.2	1.9	2.7	49.2	52.7	55.1	3.5	2.4
		Standard Deviation of Speed (mph)	4.7	4.2	8.5	-	-	5.2	4.4	8	-	-	4.4	3.9	8.9	-	-
		% Going Over Speed (%)	56.7	82.1	89.4	-	-	53.4	78.9	86.9	-	-	53.2	82.7	89.2	-	-
		% Going 5mph Over Speed (%)	14.7	32.3	52.1	-	-	13.7	26.8	41.7	-	-	12.6	34.7	48.3	-	-
4	SFS	Average Speed (mph)	43.1	42.3	43.7	-0.8	1.4	49.9	44.1	45.8	-5.8	1.7	51.1	44.1	46.6	-7	2.5
		85th Percentile of Speed (mph)	47.7	46.5	47.8	-1.2	1.3	54.7	48	49.6	-6.7	1.6	55.7	55.7	50.3	0	-5.4
		Standard Deviation of Speed (mph)	4.9	5.2	4.8	-	-	4.9	4.8	4.4	-	-	5.2	4.4	7.4	-	-
		% Going Over Speed (%)	17.8	14.8	24	-	-	17	14.3	20	-	-	23.3	15.5	31.44	-	-
		% Going 5mph Over Speed (%)	4	2.4	5.6	-	-	4.4	2.3	4.9	-	-	5.14	3.3	9.32	-	-
5	SFS	Average Speed (mph)	49.7	44.5	46.3	-5.2	1.8	49.9	44.1	45.8	-5.8	1.7	51.1	44.1	46.6	-7	2.5
		85th Percentile of Speed (mph)	54.9	48.2	50	-6.7	1.8	54.7	48	49.6	-6.7	1.6	55.7	55.7	50.3	0	-5.4
		Standard Deviation of Speed (mph)	7.2	5.2	4.1	-	-	6.7	5.7	4.6	-	-	5.1	4.1	3.9	-	-
		% Going Over Speed (%)	86.4	45.1	63.6	-	-	89	41.3	59.7	-	-	93.2	40.8	66.8	-	-
		% Going 5mph Over Speed (%)	51.4	7.7	15.5	-	-	53.2	6.8	13.14	-	-	4.8	4.3	17	-	-
6	SFS	Average Speed (mph)	51.3	54	52.5	2.7	-1.5	50.5	52.9	53.1	2.4	0.2	51.9	55.6	53.5	3.7	-2.1
		85th Percentile of Speed (mph)	58.4	58.1	56.6	-0.3	-1.5	56.5	57.5	57.1	1	-0.4	58.5	57.6	58.2	-0.9	0.6
		Standard Deviation of Speed (mph)	7.2	5.2	4.1	-	-	6.7	5.7	4.6	-	-	6.4	5.1	4.4	-	-
		% Going Over Speed (%)	55.17	50	80.1	-	-	51	78.5	78.16	-	-	63.7	88	84.3	-	-
		% Going 5mph Over Speed (%)	26.4	41.8	27.4	-	-	18.6	34.6	33.6	-	-	27.4	73.3	40.88	-	-
7	E	Average Speed (mph)	47.4	45.1	46.2	-2.3	1.1	47.7	44.5	46.1	-3.2	1.6	-	-	-	-	-
		85th Percentile of Speed (mph)	51.1	49.3	50.9	-1.8	1.6	51.4	48.3	50.1	-3.1	1.8	-	-	-	-	-
		Standard Deviation of Speed (mph)	3.9	4.2	4.1	-	-	3.7	3.7	4.1	-	-	-	-	-	-	-
		% Going Over Speed (%)	63.4	15.6	47.6	-	-	70.3	10.1	45.7	-	-	-	-	-	-	-
		% Going 5mph Over Speed (%)	20.9	4.4	14.41	-	-	24.2	2.4	45.8	-	-	-	-	-	-	-
8	E	Average Speed (mph)	42.9	45.5	43.2	2.6	-2.3	42.2	45.6	43.7	3.4	-1.9	-	-	-	-	-
		85th Percentile of Speed (mph)	47.6	50.1	49.4	2.5	-0.7	47	49.8	49.3	2.8	-0.5	-	-	-	-	-
		Standard Deviation of Speed (mph)	4.5	4.9	6.6	-	-	4.9	4.5	6.1	-	-	-	-	-	-	-
		% Going Over Speed (%)	32.7	55.6	39.6	-	-	27	52.22	43.6	-	-	-	-	-	-	-
		% Going 5mph Over Speed (%)	6	16	12.4	-	-	5.19	14.3	12.27	-	-	-	-	-	-	-
9	E	Average Speed (mph)	52.1	50.7	52.4	-1.4	1.7	53.3	51.8	54.2	-1.5	2.4	53.7	52.8	52.9	-0.9	0.1
		85th Percentile of Speed (mph)	56.7	54.9	59.1	-1.8	4.2	57.5	55.1	57.7	-2.4	2.6	57.2	55.5	55.4	-1.7	-0.1
		Standard Deviation of Speed (mph)	5.6	2.8	4.5	-	-	6.1	2.8	4.2	-	-	5.4	2.8	3.1	-	-
		% Going Over Speed (%)	73.5	57.2	70.5	-	-	78.5	51	73.8	-	-	75.8	54.5	70.2	-	-
		% Going 5mph Over Speed (%)	46.6	35	52.3	-	-	46.5	33.9	56	-	-	55	38.7	60	-	-

4.3 Comparing the Effectiveness of Speed Management Strategies

All the speed management strategies proposed in this study could be individually used as a practical and effective approach for both reducing the average speed and imposing the posted speed limit. However, agencies are looking for the most cost-effective one. To compare the effectiveness of the enforcement strategies, Analysis of Variance (ANOVA) was used. ANOVA is a simple statistical test that compares three or more groups of numbers, and test whether there is any statistically significant difference among the means of these groups.

In this project, mixed ANOVA will be incorporated to compare the effectiveness of speed management strategies. Mixed ANOVA is a subset of conventional ANOVA and is generally used when a dependent variable is measured over two or more periods and is measured under two or more conditions (Crowder, 2017). The mixed ANOVA framework used in this study consisted of a dependent variable - effect of speed enforcement strategy on average speed, within-subject variables - speed difference between Tube #2 and Tube #1, and between-subject variables - speed management strategies.

The primary underlying assumption for using traditional ANOVA is the homoscedasticity of the data. Therefore, to test the homoscedasticity of our data, Levene's test was performed. Generally, Levene's test is used to evaluate the equality of variance between two or more population groups. In this test, the null hypothesis assumes that the variances of the population groups are equal, or the groups have homogeneity of variances (Derrick et al., 2018, Brown and Forsythe, 1974). The p-value for the Levene's test was less than 0.05. Therefore, the main assumptions of the traditional ANOVA test were not satisfied. To handle this condition, a robust heteroscedastic ANOVA test, which is based on the trimmed means, is used. Robust statistical methods are innovative methods that can handle conditions where some of the underlying assumptions are not met (Wilcox, 2011, Mair and Wilcox, 2016). These methods are a revised type of mixed ANOVA, but instead of arithmetic mean, the trimmed mean is used in the data analysis. Trimmed mean is a robust alternative for the arithmetic mean. To estimate the trimmed mean, a certain percentage of data from the lower and higher part of the distribution are cut off (Mair and Wilcox, 2016). To build the robust heteroscedastic ANOVA, following consideration are made:

Consider $j = 1, \ldots, J$ as the between-subject variable, $k = 1, \ldots, K$ as the within-subject variable and Y_{ijk} as the dependent variable. In our case, J=3 shows the total number of speed management strategies (SFS, E, and SFS+E), K=3 shows the data collection points (Tube #1, Tube #2, and Tube #3), and the dependent variable (Y_{ijk}) is the effect of the speed enforcement strategy.

Since only the immediate effect of the speed enforcements are being compared, data collected from Tube #1 and Tube #2 will be used in this section. Therefore, only two within-subject as k and $k'$are assumed. Therefore, the difference score of the dependent variable could be calculated as: $D_{ijkk'} = Y_{ijk} - Y_{ijk'}$. Let θ_j be an M-estimator associated with $D_{ijkk'}$. The null hypothesis states that all speed management strategies are similarly effective. While the alternative hypothesis states that the effectiveness of at least one of the enforcement strategies is statistically different from others.

In order to compensate for the inequality of the variance, 10 percent of the means from both higher and lower tail of the data are trimmed. The resulting p-value for the ANOVA test was 0.025 and 0.007 for within-subject effects and between-subject effects, respectively. The p-values indicate that at a significance level of 0.05, there is evidence to reject the null hypothesis. That is, the effectiveness of speed management strategies is different from each other.

It is noteworthy that ANOVA is an omnibus test statistic. That is, it cannot provide information regarding which speed enforcement strategy is more effective. Therefore, to compare the effectiveness of the speed management strategies, a pairwise group comparison between every two pairs of between-subject variables is performed. R-package WRS2 is used to carry forward this test (Mair and Wilcox, 2018). The value of difference scores for each pair of speed enforcement are: $S_{(SFS+E)} - S_{(E)} = 2.4$, $S_{(SFS+E)} - S_{(SFS)} = 0.6$, and $S_{(E)} - S_{(SFS)} = -1.8$. S is the score for each enforcement strategy. Higher scores show a more effective strategy. Comparing the paired scores, it can be concluded that the speed feedback sign supported with periodic law enforcement was the most effective strategy in this study.

4.4 Halo Effect Exploration

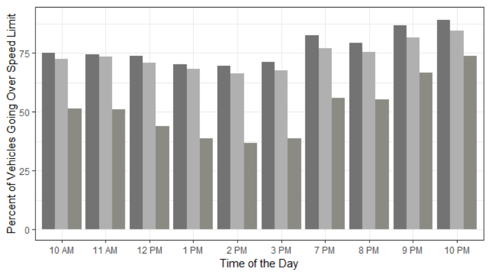
Drivers usually only abruptly decelerate their speed in the immediate vicinity of the speed management strategies, and after passing these strategies, they will quickly regain their speed. This phenomenon is called the halo effect. Therefore, in our study, the data collected from Tube #3 were used as the indicator of halo effect. In other words, by comparing the average speed of vehicles in the vicinity of the speed management strategies (Tube #2) and the average speed of vehicles after passing the speed management strategies (Tube #3), it can be observed:

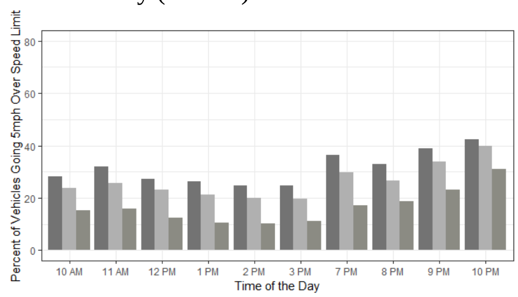
1- For the sites with only periodic law enforcement or only an SFS (Sites #4, #5, #7, and #9), the vehicles regained their speed after passing the speed management strategies (the increase of average speed was statistically significant at the 5% significance level).
2- For sites with SFS supported with periodic law enforcement (Sites #1 and #2), the vehicles tended to slow down even after the enforcement zone (the reduction of average speed was statistically significant at the 5% significance level).
3- The trend observed for Sites #1 and #2 provides statistical evidence that supporting the SFS with periodic law enforcement can increase the distance at which vehicles regain their speeds.

In addition to average speed, the proportion of vehicles exceeding the speed limit and exceeding the speed limit by at least five mph (eight km/h) for the six selected sites is shown in Figure 4.2. The left-sided plots are the bar plots for the percent of vehicles going over the speed limit at each data collection point, and the right-sided plots are the bar plots for percent of vehicles going five mph over the speed limit. It is expected to see a gradual decrease (or no change) in percent of vehicles going over the speed limit from Tube #2 to Tube #3. However, due to the existence of the halo effect, this cannot be observed for all the sites. For Sites #1 and #2 that are enforced with speed feedback sign supported by periodic law enforcement, the percent of vehicles going over the speed limit is decreasing over the data collection points.

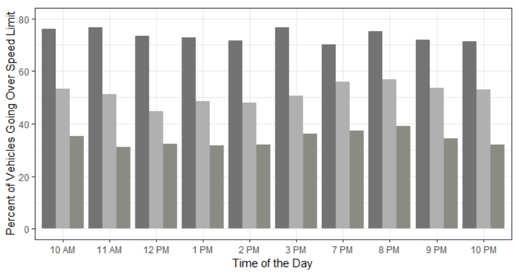
Percent of vehicles going over the speed limit	Percent of vehicles going 5mph over the speed limit

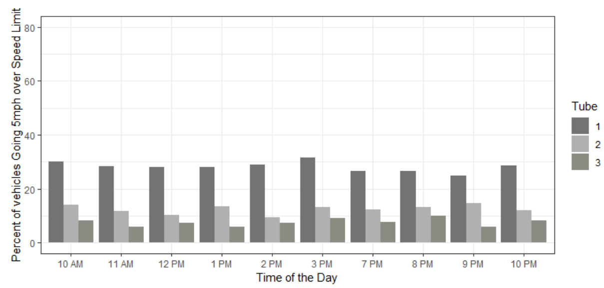
Site #1: W Ina Rd @ N Leonardo Da Vinci Way (SFS+E)



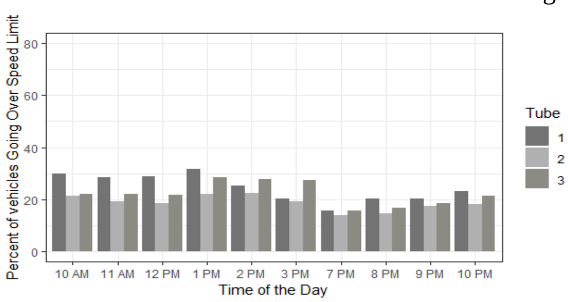


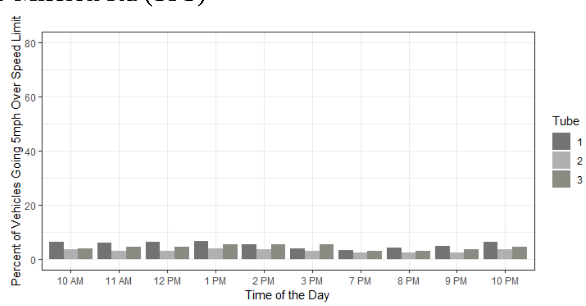
Site #2: W Ina Rd & N @ Montebella Rd (SFS+E)



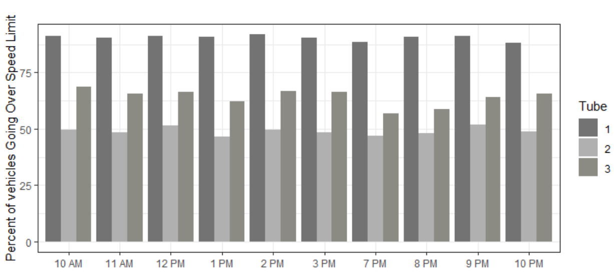


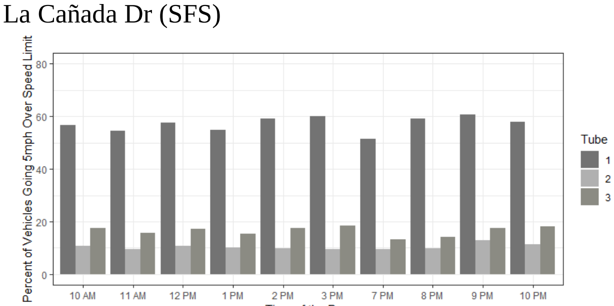
Site #4: W Irvington Rd @ S Mission Rd (SFS)



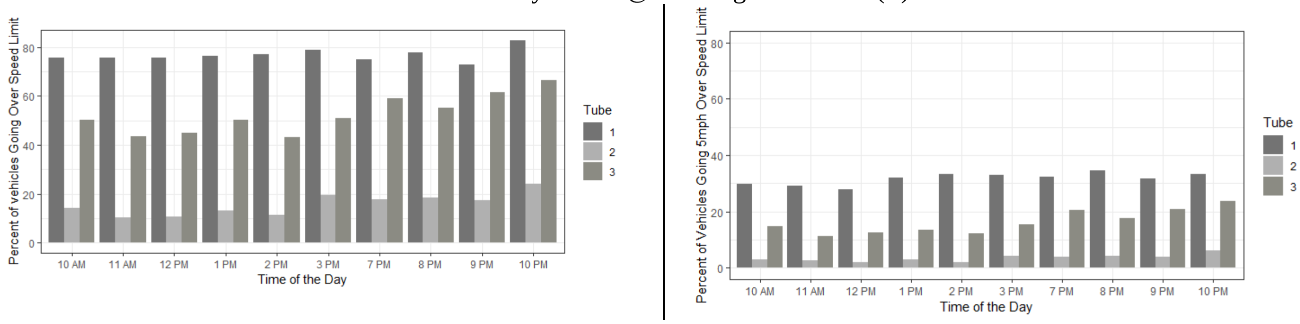


Site #5: W River Rd @ N La Cañada Dr (SFS)





Site #7: E Skyline Dr @ E Orange Grove Rd (E)



Site #9: E Camino Del Río @ N Sabino Canyon Rd (E)

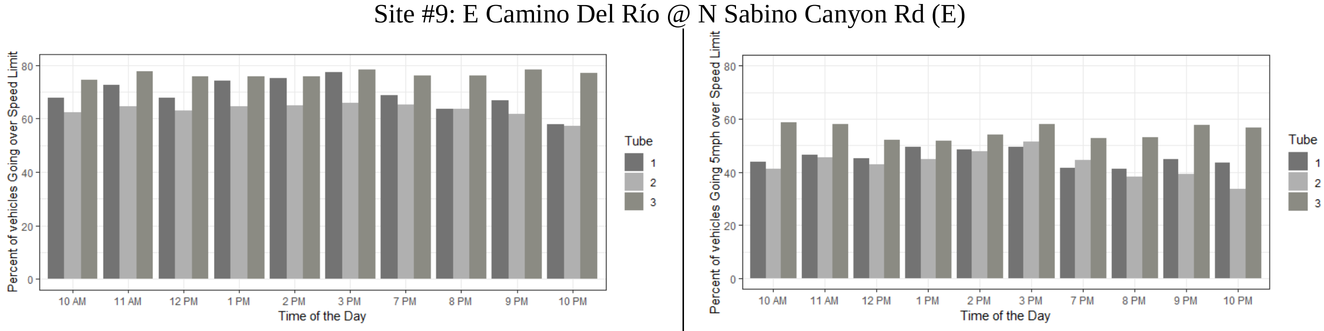


Figure 4.2 Effect on the proportion of drivers exceeding the speed limit

For Sites #4, #5, #7 and #9, the percent of vehicles going over speed limit decreased only going from Tube #1 to Tube #2 and then will increase approaching to Tube #3. Based on the illustrations in Figure 4.2, the positive impact of supporting the SFS with periodic law enforcement in eliminating the halo effect can be observed.

Chapter 5

Conclusion & Recommendation

5. CONCLUSION AND RECOMMENDATION

5.1 Conclusions

This study examined the impact of three different speed management strategies, namely: 1) Speed Feedback Sign (SFS), 2) Periodic law enforcement, and 3) SFS supported by periodic law enforcement in reducing trucks' and passenger cars' speeds. In order to evaluate the impact of each enforcement strategy, a cross-sectional study design was set up in Pima County, Arizona. In total, nine study sites were selected: three sites with SFS, three sites with periodic law enforcement, and three sites with SFS supported with periodic law enforcement.

At each study site, date, time, speed, length, and the number of vehicles axles were collected for a week. Data analysis was conducted for trucks and passenger cars separately and based on time of day and day of the week. The performance measures used in this study are: a) Average speed, b) 85th percentile speed, c) standard deviation of speed, d) proportion of vehicles exceeding the speed limit, and e) proportion of vehicles exceeding the speed limit by more than five mph (8 km/h).

The general effect of the speed management strategies (SFS, E, and SFS+E) showed that all the strategies were effective in reducing average speed and percent of drivers exceeding the speed limit. The results of comparing the effectiveness of speed management strategies showed that the speed feedback sign supported with periodic law enforcement is the most effective strategy. Further analysis of the data showed that by supporting the SFS with periodic law enforcement, the halo effect could be eliminated. The results from comparing the behavior of trucks and passenger cars also revealed similar behavior. That is, both trucks and passenger cars tend to slow down after observing the enforcement. In addition, similar speed behavior was observed during weekdays and weekends.

5.2 Recommendation

The research team successfully achieved all the project objectives. The following recommendations are provided for PCDOT for further improving arterial safety, improving the effectiveness of the current speed management strategies implemented in the county, and optimizing the county's resources.

1- The results of data analysis for this project showed that supporting SFS with periodic law enforcement is the most effective speed management strategy. It is recommended that PCDOT support all the available SFSs with periodic law enforcement if possible.

2- For the sites with special geometric and topographic conditions, none of the speed management strategies (SFS, E, and SFS+E) are effective in reducing driver's average speed. It is recommended that PCDOT use other types of speed management strategies, such as speed regulating strip, rumble strip, bumps and humps for sites with special geometric and topographic condition.

3- In this project, pneumatic road tubes were used for collecting the vehicle's speed. Tubes are visible detectors that can affect the driver's behavior while approaching them. It is recommended that PCDOT use non-intrusive detectors, such as radar-based sensors, for temporary data collection.

4- When dealing with speeding issues, generally three Es are included: Engineering, Enforcement, and Education. It is recommended that PCDOT spend more resources on the Education element for enhancing public awareness on speeding issues.

5- During the project, the research team found out that some of the newer generations of the SFS are able to collect the vehicle's speed. It is recommended that PCDOT exchange the current traditional SFS for the newer generation.

6- Currently, large-scale third-party probe-based data is available to all local and state DOTs. Future research could focus on using real-time and historical third-party probe-based data to identify the locations prone to speeding. PCDOT could benefit significantly from this type of information to relocate the law enforcement resources and optimally use all their available capacity. In addition, it is recommended that PCDOT conduct further analysis of the third-party probe-based data to identify speeding hotspots and locate the potential SFS locations in the future.

7- Future studies could target the potential impact of speed management strategies on crash frequency and severity. The results could be further investigated to estimate and compare the return of investment (ROI) of each speed management strategy.

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