Transportation Research Part F 77 (2021) 55–72

Contents lists available at ScienceDirect

Transportation Research Part F

journal homepage: www.elsevier.com/locate/trf

Effects of speed feedback signs and law enforcement on driver speed

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A R T I C L E I N F O

Article history:
Received 7 July 2020
Received in revised form 17 November 2020
Accepted 19 November 2020
Available online 18 January 2021

Keywords:
Driver speed behavior
Speed feedback sign
Periodic law enforcement

A B S T R A C T

This study analyzes the effects of implementing three speed management strategies, namely speed feedback signs, periodic law enforcement, and speed feedback sign supported with periodic law enforcement on driver speed behavior and compliance. To analyze the effectiveness of each strategy, nine locations in Pima County, Arizona, were studied in a cross-sectional framework. For each study site, the driver's speed, date, time, and vehicle's length were collected at a location prior to the speed management zone as the baseline, at the speed management zone, and downstream of the speed management zone. The general effect showed that all the strategies were effective in reducing average speed and the proportion of drivers exceeding the speed limit. In addition, the results of the robust heteroscedastic ANOVA test showed that among all the 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 average speed and proportion of drivers exceeding the speed limit would last, even after passing the speed management strategy. In other words, the existence of periodic law enforcement could potentially modify drivers' behaviors and increase the spatial effectiveness of speed feedback signs. Comparing the behavior of truck and passenger car drivers also revealed similar results. That is, both truck and passenger car drivers tend to slow down after observing the speed management strategy. The experimental evidence indicates positive benefits for reducing excessive speeding behaviors at the sites.

1. Introduction

A considerable amount of research has demonstrated a direct relationship between speed and both crash frequency and crash severity. Based on a report by the National Highway Traffic Safety Administration (NHTSA), in 2017, speeding was the contributing factor to 9,717 fatal accidents, which account for almost one-third of all motor-vehicle related fatalities in the United States (NHTSA, 2017). In addition, it has been shown that the risk of a fatal collision at 31 mph is more than two times of a collision at 25 mph and five times of a collision at 19 mph (Rosén & Sander, 2009). Therefore, speed management strate-

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https://doi.org/10.1016/j.trf.2020.11.011
1369-8478/

gies to impose the speed limit and tackle speeding by changing drivers' speed behavior are important for transportation agencies to implement. Speed feedback signs (SFS), law enforcement, and automated speed enforcement cameras are some of the most common speed management strategies that have been adopted widely.

Although studies have largely shown these strategies are effective (Karimpour et al., 2020; Medina et al., 2009; Santiago-Chaparro et al., 2012; Vaa, 1997), there is still debate regarding the extent of the effectiveness of fixed-point speed management strategies (e.g., SFS, enforcement camera) compared to section-based speed management strategies (e.g., Average section speed control) (Champness et al., 2005; De Pauw et al., 2014b). The drawback of the fixed-point speed management strategies is that many drivers only reduce their speed in the immediate vicinity of the speed management strategies before they quickly regain their speed (De Pauw et al., 2014b). Moreover, while speed cameras are one of the most cost-effective solutions to impose speed change, they are not widely used in the United State due to the current political climate (Retting et al., 2008). The continuous presence of enforcement officers is cost-prohibitive to many agencies. Therefore, there still exists a need for developing an applicable and cost-effective speed management strategy.

This study was initiated to evaluate alternative methods for modifying speed behavior and compliance in Pima County, Arizona. Transportation and policing agencies in the state of Arizona have largely shied away from using automated enforcement technology such as red-light cameras due to the elected leadership. Aside from pressure from state leadership, agencies tended to have trouble enforcing the fines from the automated systems. Nevertheless, speed control is one of the most significant factors in mitigating traffic crash frequency and severity. Without the use of speed enforcement cameras, there is a need to determine other best practices for addressing drivers' speeding behavior. Therefore, this study proposed a new speed management strategy of supporting SFS with periodic law enforcement. The proposed strategy takes advantage of the strengths of both methods. The main objective of this research was to determine if periodic law enforcement presence at SFS could be used to boost the effectiveness of SFS while remaining cost-effective. To analyze the effectiveness of the proposed strategy, nine locations in Pima County, Arizona, with a combination of speed management strategies (SFS, periodic law enforcement, and SFS supported by periodic law enforcement) were studied in a cross-sectional framework. For each study site, the driver's speed, date, time, vehicle's length, and the number of vehicle axles were collected for one week at a location prior to the speed management zone, at the speed management zone and downstream of the speed management zone.

2. Literature review

A straightforward solution to enhance the safety and mobility of the transportation network would be constructing new roads or adding additional lanes to the existing roads. However, due to the limited infrastructure and high construction cost, this solution is not always viable. Recently, with the emergence of new technologies, ITS solutions, and various data-driven approaches, transportation agencies are actively seeking to utilize ubiquitous technologies to improve mobility and safety on their roadway network. Advanced traveler information systems, such as dynamic message signs (Jeihani et al., 2018), real-time crash prediction (Ariannezhad et al., 2020), ramp metering control strategies (Ma, Karimpour, & Wu, 2020), micro and macro-level safety analysis (Ariannezhad & Wu, 2019; Ariannezhad et al., 2020; Eftekharzadeh & Khodabakhshi, 2014; Hosseinzadeh, Karimpour, Kluger, & Orthober, 2020), and crash prediction and hotspot analysis (Mansourkhaki et al., 2017; Mansourkhaki et al., 2017; Mousavi et al., 2019) are some of the innovative data-driven approaches recently adopted by transportation agencies. However, for imposing speed limits generally speed management strategies are being utilized.

Speed management strategies are multi-disciplinary approaches that control and regulate driver's speed and speeding behavior using enforcement, road design, and technology applications (Bagdade et al., 2012). NHTSA defines speed management strategies as a balanced program that involves the relationship between speed, speeding, and safety (NHTSA, 2006). The main goal of every speed management strategy is to improve traffic mobility, public health, and traffic safety while maintaining a limited budget (NHTSA, 2014). Traffic calming (FHWA, 2014; FHWA, 2011; Vanwagner et al., 2011), speed feedback signs (Lee, 2006; Santiago-Chaparro et al., 2012), law enforcement (Habibian et al., 2015; Sisiopiku & Patel, 1999; Vaa, 1997), average section speed control (De Pauw et al., 2014a; Retting et al., 2008), and speed enforcement cameras (De Waard & Rooijers, 1994; Jones & Lacey, 1997; Novoa, 2010) are some of the most common speed management strategies used by transportation agencies.

According to Federal Highway Administration, the goals of traffic calming strategies are to reduce driver's speed, reduce conflict between motor vehicles, and improve cyclists' and pedestrians' safety, mobility, and comfort (FHWA, 2011; Habibian & Hosseinzadeh, 2018; Hatamzadeh & Hosseinzadeh, 2020). Roadway design is one type of traffic calming strategy that is currently being used in different States (Kaplan & Robards, 2002; NHTSA, 2005). Reducing street width, speed humps, traffic circles, transverse pavement markings, and transverse rumble strips are different types of roadway designs that will help to calm the traffic. In general, the specifics of installing roadway design countermeasures and their safety foci are different. The location of installation can vary from lower-speed neighborhoods to major arterials and rural roadways, and the safety focus could be for pedestrian safety, roadway departure, or intersection. A considerable amount of studies focused on the effectiveness of using speed hump, road diet, speed tables, and traffic circles on urban roads with lower operating speed. These studies showed that such countermeasures are effective in reducing speed and crash reduction in urban areas with lower speeds (NHTSA, 2005; Schultz et al., 2008; Vaa & Truls, 2004).

The effect of installing transverse pavement markings and transverse rumble strips have also been studied through the NCHRP project 3–74. These countermeasures were evaluated based on a before-and-after field study over several sites in Oregon and Texas (Ray et al., 2007). Transverse pavement markings were effective in reducing mean speed by 0.9 mph on stop-controlled and uncontrolled approaches and were effective in reducing mean speed by 20–30 percent at horizontal curves, roundabout approaches, work zones, highway off-ramps, and bridges in Oregon. The effectiveness of converging chevrons was also studied at a single-direction freeway-to-freeway exit ramp on I-94 in Milwaukee, Wisconsin. Drakopoulos and Vergou (2003) conducted a before and after study framework and used mean and 85th percentile speed as their performance measures. After the installation of the converging chevron markings, the mean speed was reduced by 15 mph, and the 85th percentile speed was reduced by 17 mph (Drakopoulos & Vergou, 2003).

Speed feedback signs (SFS), or dynamic speed display signs, are one of the most popular fixed speed management strategies. SFSs are interactive signs that display the approaching speed until it surpasses a predefined threshold, after which the signs will alert the driver of speeding through either a word message of "Slow Down" or a flashing light. SFS are mainly deployed for traffic calming at locations with a history of extreme over speeding (Cruzado & Donnell, 2009; Karimpour et al., 2020), sensitive road segments such as work zones (Ullman & Rose, 2005) and school zones (Lee et al., 2006), or in locations where failure to comply with the speed limit can be especially hazardous due to the geometric road designs such as curves or operational changes such as speed transition zones (Cruzado & Donnell, 2009). Compared to other strategies, SFSs are low-cost and effective in influencing driver speed behavior (Gehlert et al., 2012).

The impact of installing SFS on work zones has been investigated by several researchers. Pesti and McCoy studied SFSs along a 2.7-mile work zone on I-80. Their results showed a statistically significant reduction in driver speed and an increase in speed limit compliance during the study period (Pesti & McCoy, 2001). In another study, Carlson et al. (Carlson et al., 2000) evaluated the impact of speed trailers at high-speed temporary work zones. The results of this study also showed that SFS could reduce the speed in the work zone by about 5 mph (Carlson et al., 2000). The impact of implementing SFS on school zones was also investigated in a before-and-after study by Ulman and Rose (2005). The authors installed multiple SFSs in school zones and on horizontal curves and showed that SFSs were effective in reducing the average speed by 9-mph in school zones and less than 5-mph on horizontal curves (Ullman & Rose, 2005). Lee et al (2006) examined SFSs in two school zones and examined the impact of SFS during the short term after installation. The results showed that an SFS was able to reduce the average speed by 17.5% throughout the day (Lee et al., 2006).

Some recent studies concentrate on evaluating the impact of installing SFS on urban and rural areas. Karimpour et al. (Karimpour et al., 2020) evaluated the impact of installing SFS on high-speed arterial in Arizona. The authors showed that SFSs can be effective in reducing the link-speed (Karimpour et al., 2020). In another study, Zineddin et al. (2016) evaluated the impact of installing SFS on 20 rural two-lane roadways with a history of high crashes. The results of this study showed SFSs are effective in reducing the average and 85th percentile of speed. In addition, the results of this study demonstrated a significant reduction in the number of vehicles traveling over speed limits (Zineddin et al., 2016). In a similar study, Hallmark et al. (2016) evaluated the short-term and long-term effectiveness of SFSs on average speed and crash reduction in multiple states. The results of this study showed the average speed reduced by 1.82 mph, 2.57 mph, and 1.97 mph on average for all the sites, for 1, 12, and 24 months after signs installation. In addition, the results of their study suggested a crash modification factor of 0.9 to 0.95 for SFS (Hallmark et al., 2015).

The impact of different types of SFS on driver speeding behavior was also evaluated in a study in Germany. Three types of SFS: (a) SFS showing driver's actual speed; (b) SFS showing driver's actual speed and speed limit; and (c) a verbal SFS with the word "Thank You" when the car driver kept the speed limit and the word "SLOW" when the driver exceeded the speed limit. The results showed that all three types were effective in reducing average speed, 85th percentile of speed, and the percentage of vehicles exceeding the speed limit (Gehlert et al., 2012).

Onsite law enforcement is another common strategy effective in reducing driver speed and increasing speed limit compliance (Holland & Conner, 1996; Stanojević et al., 2018; Van Houten & Malenfant, 2004). A study found that using random physical law enforcement can reduce the average speed by two mph to three mph (Elliott & Broughton, 2005). Walter et al. (2011) examined the impact of increased law enforcement on a route in south London and found out that increasing law enforcement reduced the average and extremely high speeds along the route. An increase in law enforcement was also examined in Queensland, Australia, through a program called Road Safety Initiatives Package (RSIP) (Newstead et al., 2004). The authors found that implementing the RSIP program can reduce a large portion of drivers exceeding the speed limit in a 40 mph zone. In addition, it has been shown that regular enforcement can change drivers' behavior and increase the spatial effects of the enforcement up to 1.5 miles to 5 miles downstream of the enforcement sites (Elliott & Broughton, 2005; Newstead et al., 2004), much longer than other fixed speed management strategies. The impact of different enforcement units on drivers' behaviors was also evaluated in a study by Dowling and Holloman (Walter, 2009; Dowling & Holloman, 2008). The results of this study showed that unmarked enforcement could reduce average speed significantly if the law enforcement unit is positioned in a place where the motorist is surprised by their presence (Dowling & Holloman, 2008). In another study, Hajbabaie et al. (2009) evaluated whether enforcement units with lights off are also effective in reducing speeding. The authors evaluated their findings based on various degrees of speeding (e.g., moderate speeding, extensive speeding) in two work zones interstates in Chicago, IL. The results of this study showed that the speed reductions were slightly higher in the extensive-speeding site (Hajbabaie et al., 2009). However, the main drawback of law enforcement is the limited enforcement resources and high costs, and it is mostly impractical to implement onsite law enforcement regularly in all the needed areas.

Average section speed control and camera enforcement are other types of speed management strategies that are deployed widely in different states. The advantage of average section speed control is that the average driving speed will be recorded (De Pauw et al., 2014a). De Pauw et al. (2014a) evaluated the effectiveness of this strategy on a three-lane motorway with a speed limit of 75 mph in Flanders, Belgium, through a before-and-after study. The results of this study showed a significant reduction of 3.63 mph 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 Average section speed control program implemented in Montgomery County, Maryland. The authors collected speeds for six months before and after implementing the speed strategy. The results of their study showed that this strategy is effective in reducing the percent of drivers going over the speed limit (Retting et al., 2008).

This section introduced the highlights of several types of speed management strategies, namely: 1) Traffic calming design, 2) SFS, 3) law enforcement, and 4) average section enforcement using speed cameras. Based on the evaluation results of the previous studies, all these strategies are effective in monitoring and modifying driver speed behavior and compliance. However, each of these strategies has its drawbacks. Traffic calming strategies are not always applicable to high-speed arterials and the environmental and noise pollutions caused by some of these strategies, which limits engineers from installing it on many road segments. A major issue with SFSs is that drivers only abruptly decelerate their speed in the immediate vicinity of the speed management strategies, and after passing it, they will quickly regain their speed (De Pauw et al., 2014b). Law enforcement is very costly, and some jurisdictions might have limited enforcement resources. No previous studies were identified that investigated how periodic enforcement could impact speeding at SFSs.

3. Methodology

3.1. Experimental design and site selection

This study aimed to analyze the effects of three speed management strategies, namely: 1) Speed feedback signs (SFS), 2) Periodic law enforcement (E), 3) Speed feedback signs supported by periodic law enforcement (SFS+E), on driver speed behavior and compliance. Periodic law enforcement is defined as intermittently enforcing the speed throughout a specific time period. For this study, Pima County Police Department oversaw law enforcement. The sheriff lieutenants were asked to stay at the police pullout periodically throughout the data collection of each site. In order to evaluate the effects of each strategy on driver speed behavior, nine sites were selected in Pima County, Arizona: three sites with SFS, three sites with periodic law enforcement, and three sites with SFS supported with periodic law enforcement.

For the sites with SFS-only and SFS+E, the SFSs used were fixed black and white rectangular signs with "YOUR SPEED" text above the display. The signs were paired with speed limit signs for driver reference (Fig. 1).

For the periodic law enforcement-only and SFS+E sites, sheriff's deputies were asked to enforce the sites either with a motorcycle or a fully marked motor vehicle. Based on the size of the police pullouts, the deputies decided the enforcement vehicle type to use. For the sites with SFS+E, the pullout was located in a range of 100–200 ft after the SFS sign (police pullouts were visible from the SFS signs). Fig. 2 illustrates a sample police pullout in Pima County, AZ.

Detailed information regarding the study sites is provided in Table 1. It should be noted that for selecting the study sites, the Pima County Dept. of Transportation and Sheriff's Dept. have several restrictions: 1) for the sites with SFS and SFS+E strategy, the site needed to have an active speed feedback sign, 2) the site needed to have a police pullout in the vicinity

Fig. 1. Speed feedback sign used in this study.

Fig. 2. Police pullout located at W Ina Rd. @ N Leonardo Da Vinci Way.

Table 1
Study sites description.

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	EB	45	Normal	221,099	04/19/2019 04/26/2019
2	W Ina Rd & N @ Montebella Rd	SFS+E	EB	45	Normal	136,890	11/13/2018 11/20/2018
3	1st @ Rudasill Rd.	SFS+E	SB	45	Downgrade	208,550	02/26/2019 03/05/2019
4	W Irvington Rd. @ S Mission Rd.	SFS	SB	45	Normal	217,792	04/08/2019 04/15/2019
5	W River Rd. @ N La Cañada Dr.	SFS	WB	45	Normal	239,554	04/30/2019 05/07/2019
6	S Houghton Rd. @ E Bekke Rd.	SFS	SB	50	Curvature and side street entrance in the vicinity of the second Tube	96,677	04/09/2019 04/15/2019
7	E Skyline Dr. @ E Orange Grove Rd.	E	EB	45	An intersection in the vicinity of the second Tube	161,524	12/04/2018 12/11/2018
8	E Sunrise Dr. @ Hacienda Del Sol Rd.	E	EB	45	Downgrade	178,381	12/04/2018 12/11/2018
9	E Camino Del Río @ N Sabino Canyon Rd.	E	NB	40	Normal	299,797	05/14/2019 05/21/2019

of the speed feedback sign, and 3) high-risk locations were off-limits since the sheriff lieutenants were not able to monitor or enforce the speeds safely.

€In order to only identify the effects of proposed strategies and eliminate other confounding factors, the information regarding geometric and topographic conditions of each site is also provided in this table. Further information about the study sites, data collection points, geometric designs, and the distance between each pair of tubes are provided in Fig. 3.

The speed limits of most of the selected sites are 45 mph. The first two sites (Sites 1 & 2) are located in a major west-east corridor connecting the east side of Tucson to Interstate 10. This corridor is a multimodal arterial with high volumes of passenger cars, transit, and pedestrian activity. Site 3 is located in a north–south corridor, connecting two major east–west corridors. Sites 4, 7, 8, and 9 are located on high-speed signalized arterials. Site 5 is a major east-west signalized corridor. Site 6 is a high-speed signalized arterial connecting the north side of Tucson to Interstate 10.

3.2. Data collection

At each study site, data was recorded at three points along the segment: a) Baseline Data Collection (BDC) point: prior to the speed management strategy point, where the speed management was not visible, b) Speed Management Strategy Data Collection (SMDC) point: located in the vicinity of the speed management strategy, and c) Downstream Data Collection (DDC) point: located downstream of the speed management strategy. A similar setting was used for all the study sites with speed management treatments, as shown in Fig. 4.

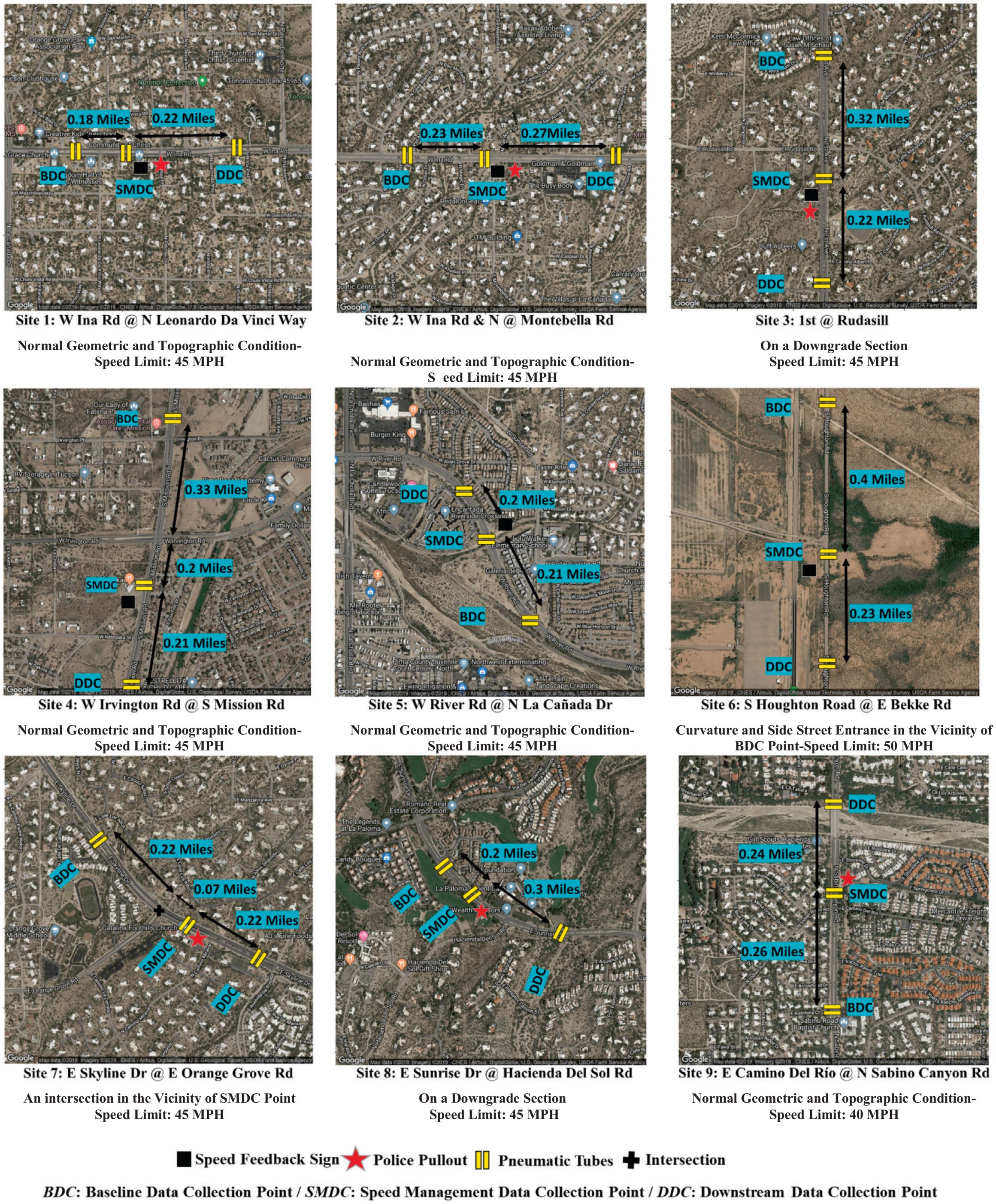

Fig. 3. Study sites locations.

For each data collection point, a pair of pneumatic tubes were installed. The tubes were one foot away from each other, and both were connected to a controller on the side of the roadway. The controller recorded the elapsed time of a vehicle passing the first and second tubes and then calculate the vehicle speed, the number of axles, and length. The controller collecting the data from the tube was a small black box locked to a fixed object, such as a tree. The driver's speed, date, time, vehicle's length, and the number of vehicle axles were collected using these pneumatic tubes.

The data collection points were selected based on the following preconditions:

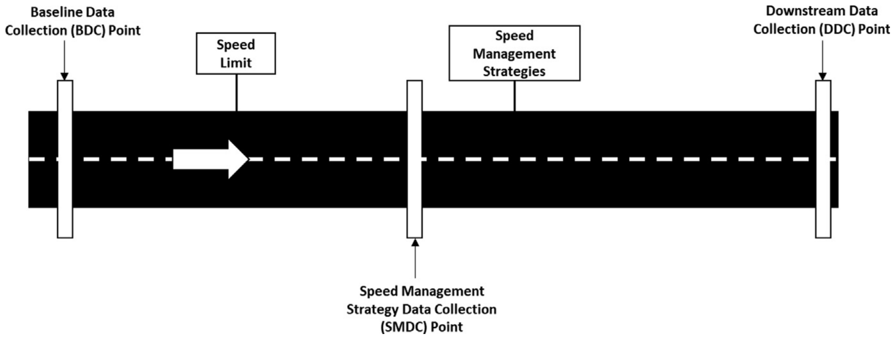

Fig. 4. Data collection set up.

1- At the BDC point driver should not be able to see the speed management strategy
2- SMDC should be in the vicinity of the speed management strategy; this data collection point was within 100 feet of the speed management strategy.
3- A nearby light pole or tree was required to lock the pneumatic tube's controller
4- The distance between SMDC and DDC points should not be shorter than 166 m (0.09 miles), which was estimated based on the standard value of the acceleration rate for regular passenger cars suggested by Hardwood et al. (1996).

3.3. Law enforcement

For this study, the Pima County Sheriff's Department (PCSD) oversaw law enforcement. The Sheriff's lieutenant was only asked to enforce the location intermittently throughout the study period without any specific pattern; the lieutenant was in charge of his deputies to enforce the study site. Periodic enforcement could help the PCSD to optimize its law enforcement resources more efficiently. In addition, it might also indirectly influence frequent travelers' subconscious and lead them to be cautious even after passing any SFS. The sites with SFS+E and E strategy were enforced up to one-hour per day. Table 2 illustrates some sample logs recorded by Sheriff's Deputies at Site 2 enforced with SFS and periodic law enforcement.

4. Results

This section provides detailed information on evaluating the effectiveness of the study speed management strategies in terms of driver speed behavior and driver compliance. Initially, a series of heatmap plots are developed to highlight the driver speed behavior while approaching each of the speed management strategies. Next, the detailed statistical method used for speed management assessment and comparison is provided. Finally, the halo effect exploration (i.e., spatial effectiveness of speed management strategies) are examined.

4.1. Preliminary data analysis

In order to get a better insight into the driver speed behavior during the day, heat maps are produced for all the study locations. Based on the heat map produced for each location, one can observe how driver speed behavior changes during the day. It is noteworthy that the speed data is aggregated in a one-hour duration for producing the heat maps in Fig. 5. The green colors represent vehicles with an average speed equal or lower than the speed limit (more favorable conditions), and red colors represent vehicles with an average speed higher than the speed limit (less favorable conditions).

Table 2
A Sample Log of the Law Enforcement at Site 2.

Site 2: W Ina Rd & N @ Montebella Rd (SFS+E)				
Date	Time	Enforcement Vehicle type	Traffic Stops	Citations
11/13/18	1632–1702	Fully marked motorcycle	1	1
11/15/18	0800–0900	Full-sized, fully marked vehicle	1	1
11/18/18	0810–0825	Full-sized, fully marked vehicle	0	0
11/18/18	0630–0700	Fully marked motorcycle	0	0
11/19/18	0810–0840	Full-sized, fully marked vehicle	0	0
11/20/18	0130–0155	Full-sized, fully marked vehicle	0	0
11/20/18	0645–0730	Full-sized, fully marked vehicle	2	2

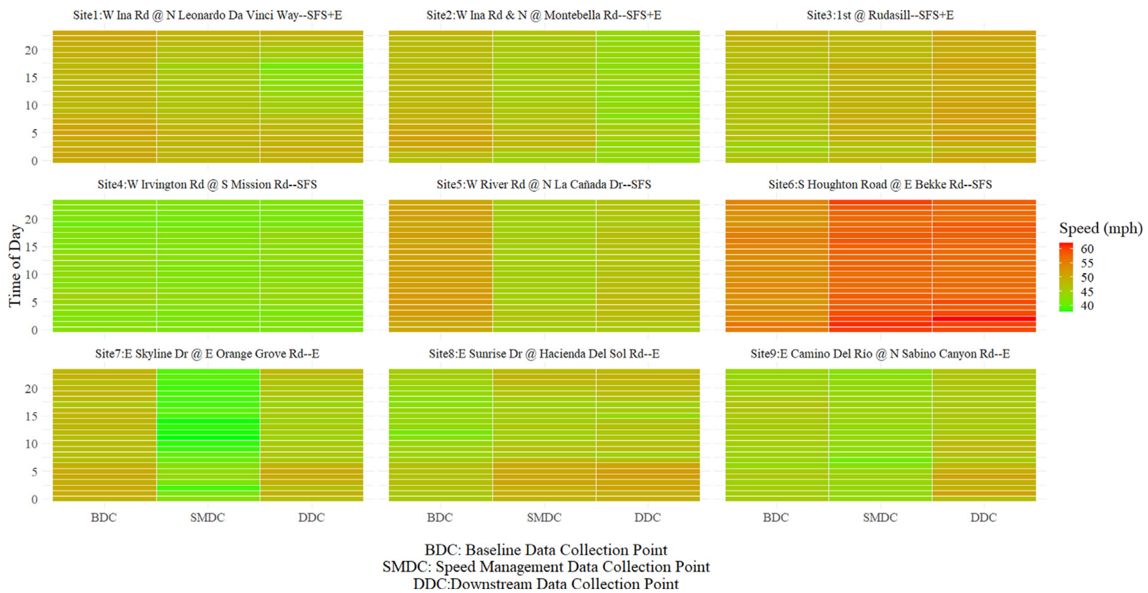

Fig. 5. Driver speed behavior based on time of day.

Based on Fig. 5 at nighttime (from midnight to 6 am), in almost all the study locations, drivers are operating at a higher speed compared to other times of the day. In most of the study locations, drivers tend to slow down in the vicinity of the speed management strategy and regained their speeds after passing it. It is important to note that the reason behind a darker heatmap for site 6 is the higher speed limit for this site. The speed limit at all sites is 45 mph, except for site 6 which is 50 mph, and site 9 which is 40 mph. Further detailed information regarding speed distribution based on time-of-day, day-of-week, and vehicle classification are provided in Tables 3 and 4.

4.2. Assessment of speed management strategies

To evaluate the effectiveness of the proposed speed management strategies in detail, two measures of driver speed behavior and two measures of speed limit compliance were considered. The average speed difference between the baseline data collection point (BDC) and the speed management data collection point (SMDC) and the average speed difference between the speed management data collection point (SMDC) and the downstream data collection point (DDC) correspond to the driver behavior measures. The proportion of vehicles going over the speed limit and the proportion of vehicles going 5 mph over the speed limit relate to the compliance measure. The first category (proportion of vehicles going over the speed limit) accounts for the percentage of all vehicles going over the speed limit, while the second category, (proportion of vehicles going 5 mph over the speed limit) accounts for only vehicles going 5 mph or more over the speed limits. In addition, to consider the traffic pattern change during peak, off-peak, weekday, and weekends, the data were carefully divided into several categories as below:

- 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)

To ensure that vehicle types do not impact the results of the study, truck and passenger car drivers' behavior was analyzed independently. Tables 3 and 4 present the average speed, proportion of drivers exceeding the speed limit, and proportion of drivers exceeding the speed limit by more than 5 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).

The immediate effect is the average speed difference between the speed collected at the baseline (BDC) and the speed management zone (SMDC). The secondary effect is the average speed difference between the speed collected at the SMDC and the DDC point. A negative value for immediate and secondary effects indicates that the drivers speed up after passing the speed management zone, and the positive values indicate that the drivers slow down after passing the speed management zone.

To examine the significance of average driver speed behavior change after the speed management strategies, a *t*-test was used. The reason for selecting a *t*-test is that based on the central limit theorem when the sample size is large, the mean of the response variable is approximately normally distributed, therefore the assumption of a *t*-test is appropriate. In developing Tables 3 and 4, hypotheses tests were conducted for both immediate and secondary effects. For the immediate effect, the

Table 3
Effect of Different Speed Management Strategies on Passenger Cars.

Passenger Cars			Weekday										Weekend				
			Peak Hour					Off-Peak Hour					Day				
Site	Speed Management Strategy	Measures	BDC	SMDC	DDC	Immediate Effect (mph)	Secondary Effect (mph)	BDC	SMDC	DDC	Immediate Effect (mph)	Secondary Effect (mph)	BDC	SMDC	DDC	Immediate Effect (mph)	Secondary Effect (mph)
1	SFS+E	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
		Prop. of Going Over Speed Limit (%)	73.2	72.2	45.7	–	–	72.5	70	49.21	–	–	74.4	72	53.7	–	–
		Prop. of Going 5mph Over Speed Limit (%)	27.9	26.3	15.3	–	–	26.7	26.1	15.46	–	–	30	31.8	18.4	–	–
		Sample Size (Passenger Car)	54,369					81,701					37,212				
2	SFS+E	Average Speed (mph)	48.4	45.9	43.3	−2.50	−2.60	47.8	45.4	43.3	−2.4	−2.1	–	–	–	–	–
		Prop. of Going Over Speed Limit (%)	77.6	55.2	33.14	–	–	74.8	51	35.2	–	–	–	–	–	–	–
		Prop. of Going 5mph Over Speed Limit (%)	34.2	15.2	7	–	–	29.9	12.7	7.8	–	–	–	–	–	–	–
		Sample Size (Passenger Car)	47,272					60,298					11,897				
3	SFS+E	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
		Prop. of Going Over Speed Limit (%)	67.2	87.4	92.8	–	–	65.2	82.7	90.3	–	–	74.4	88.2	91.9	–	–
		Prop. of Going 5mph Over Speed Limit (%)	20.5	40.5	55.8	–	–	20.5	33.6	48.2	–	–	30	38.1	51.1	–	–
		Sample Size (Passenger Car)	61,684					72,768					33,298				
4	SFS	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
		Prop. of Going Over Speed Limit (%)	27.8	23.7	30	–	–	25.9	20	23.9	–	–	30.3	22.5	34.7	–	–
		Prop. of Going 5mph Over Speed Limit (%)	65	3.8	6	–	–	5.63	3.3	4.6	–	–	6.9	3.8	9.5	–	–
		Sample Size (Passenger Car)	57,878					85,215					32,390				
5	SFS	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
		Prop. of Going Over Speed Limit (%)	91.6	54.5	72.7	–	–	91.4	51.5	66.5	–	–	92.9	53	72.8	–	–
		Prop. of Going 5mph Over Speed Limit (%)	61.9	12.9	23.3	–	–	59.1	11.42	17.9	–	–	63.4	12.5	22.8	–	–
		Sample Size (Passenger Car)	62,410					97,870					32,906				

(*continued on next page*)

Table 3 (*continued*)

Passenger Cars			Weekday										Weekend				
			Peak Hour					Off-Peak Hour					Day				
Site	Speed Management Strategy	Measures	BDC	SMDC	DDC	Immediate Effect (mph)	Secondary Effect (mph)	BDC	SMDC	DDC	Immediate Effect (mph)	Secondary Effect (mph)	BDC	SMDC	DDC	Immediate Effect (mph)	Secondary Effect (mph)
6	SFS	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
		Prop. of Going Over Speed Limit (%)	82.4	94.6	96	–	–	78	93.9	94.7	–	–	80.5	96.1	93	–	–
		Prop. of Going 5mph Over Speed Limit (%)	42.4	72.2	70	–	–	35.6	70.8	67.3	–	–	42.7	80.5	65.6	–	–
		Sample Size (Passenger Car)	29,456					35,263					19,388				
7	E	Average Speed (mph)	48.4	45.6	46.8	−2.80	1.20	48.6	45.1	46.2	−3.5	1.1	–	–	–	–	–
		Prop. of Going Over Speed Limit (%)	74.1	23.6	54.3	–	–	78.5	23.5	51.4	–	–	–	–	–	–	–
		Prop. of Going 5mph Over Speed Limit (%)	30	5.8	17.9	–	–	33.6	5.8	15.6	–	–	–	–	–	–	–
		Sample Size (Passenger Car)	45,552					53,259					–				
8	E	Average Speed (mph)	44.2	46.7	45.5	2.50	−1.20	43.5	46.6	45.6	3.1	−1.0	–	–	–	–	–
		Prop. of Going Over Speed Limit (%)	43.1	63.4	55.2	–	–	37.9	63	55.5	–	–	–	–	–	–	–
		Prop. of Going 5mph Over Speed Limit (%)	4.9	23.2	22	–	–	9	21.7	20.3	–	–	–	–	–	–	–
		Sample Size (Passenger Car)	56876					65242					–				
9	E	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
		Prop. of Going Over Speed Limit (%)	72.2	58.3	71.3	–	–	74.3	50.8	72.19	–	–	75.8	58.4	72.8	–	–
		Prop. of Going 5mph Over Speed Limit (%)	45.6	36.8	56.5	–	–	46.5	34.5	57	–	–	53.5	35.6	59.8	–	–
		Sample Size (Passenger Car)	87,937					99,313					49,395				

Table 4
Effect of Different Speed Management Strategies on Trucks.

Trucks			Weekday										Weekend				
			Peak Hour					Off-Peak Hour					Day				
Site	Speed Management Strategy	Measures	BDC	SMDC	DDC	Immediate Effect (mph)	Secondary Effect (mph)	BDC	SMDC	DDC	Immediate Effect (mph)	Secondary Effect (mph)	BDC	SMDC	DDC	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
		Prop. of Going Over Speed Limit (%)	62.5	65	39.64	–	–	59.4	65.1	40	–	–	65.7	73.7	48.8	–	–
		Prop. of Going 5mph Over Speed Limit (%)	18.3	19.2	10.5	–	–	17.18	18.7	11.12	–	–	20.9	21.7	14.6	–	–
		Sample Size (Passenger Car)	7,268					9,098					3,697				
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	–	–	–	–	–
		Prop. of Going Over Speed Limit (%)	72.5	47.5	24.2	–	–	68.1	42.2	27.9	–	–	–	–	–	–	–
		Prop. of Going 5mph Over Speed Limit (%)	28.3	10.6	3.9	–	–	23.6	9.4	5.13	–	–	–	–	–	–	–
		Sample Size (Passenger Car)	6,321					6,218					1,034				
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
		Prop. of Going Over Speed Limit (%)	56.7	82.1	89.4	–	–	53.4	78.9	86.9	–	–	53.2	82.7	89.2	–	–
		Prop. of Going 5mph Over Speed Limit (%)	14.7	32.3	52.1	–	–	13.7	26.8	41.7	–	–	12.6	34.7	48.3	–	–
		Sample Size (Passenger Car)	5,964					6,388					2,349				
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
		Prop. of Going Over Speed Limit (%)	17.8	14.8	24	–	–	17	14.3	20	–	–	23.3	15.5	31.44	–	–
		Prop. of Going 5mph Over Speed Limit (%)	4	2.4	5.6	–	–	4.4	2.3	4.9	–	–	5.14	3.3	9.32	–	–
		Sample Size (Passenger Car)	6,813					7,364					2,712				

(*continued on next page*)

Table 4 (*continued*)

Trucks			Weekday										Weekend				
			Peak Hour					Off-Peak Hour					Day				
Site	Speed Management Strategy	Measures	BDC	SMDC	DDC	Immediate Effect (mph)	Secondary Effect (mph)	BDC	SMDC	DDC	Immediate Effect (mph)	Secondary Effect (mph)	BDC	SMDC	DDC	Immediate Effect (mph)	Secondary Effect (mph)
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
		Prop. of Going Over Speed Limit (%)	86.4	45.1	63.6	–	–	89	41.3	59.7	–	–	93.2	40.8	66.8	–	–
		Prop. of Going 5mph Over Speed Limit (%)	51.4	7.7	15.5	–	–	53.2	6.8	13.14	–	–	4.8	4.3	17	–	–
		Sample Size (Passenger Car)	7,255					9,530					2,923				
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
		Prop. of Going Over Speed Limit (%)	55.17	50	80.1	–	–	51	78.5	78.16	–	–	63.7	88	84.3	–	–
		Prop. of Going 5mph Over Speed Limit (%)	26.4	41.8	27.4	–	–	18.6	34.6	33.6	–	–	27.4	73.3	40.88	–	–
		Sample Size (Passenger Car)	921					1,122					435				
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	–	–	–	–	–
		Prop. of Going Over Speed Limit (%)	63.4	15.6	47.6	–	–	70.3	10.1	45.7	–	–	–	–	–	–	–
		Prop. of Going 5mph Over Speed Limit (%)	20.9	4.4	14.41	–	–	24.2	2.4	45.8	–	–	–	–	–	–	–
		Sample Size (Passenger Car)	8,214					9,924					–				
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	–	–	–	–	–
		Prop. of Going Over Speed Limit (%)	32.7	55.6	39.6	–	–	27	52.22	43.6	–	–	–	–	–	–	–
		Prop. of Going 5mph Over Speed Limit (%)	6	16	12.4	–	–	5.19	14.3	12.27	–	–	–	–	–	–	–
		Sample Size (Passenger Car)	8,012					9,976					–				
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
		Prop. of Going Over Speed Limit (%)	73.5	57.2	70.5	–	–	78.5	51	73.8	–	–	75.8	54.5	70.2	–	–
		Prop. of Going 5mph Over Speed Limit (%)	46.6	35	52.3	–	–	46.5	33.9	56	–	–	55	38.7	60	–	–
		Sample Size (Passenger Car)	9,499					8,240					3,796				

null hypothesis (H_0)states that the baseline average speed is equal to the average speed collected at the speed management point, while the alternative hypothesis (H_a)states that the baseline average speed is not equal to the average speed collected at the speed management point. Similar null and alternative hypotheses were developed for secondary effects. For this study, a confidence interval of 95% was chosen. 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, for sites 1, 2, 4, 5, and 9, which have no specific geometric and topographic conditions of note, the speed management strategies were effective in reducing the average driver speed going from BDC to SMDC. Although the speed range is different during weekdays and weekends, drivers' speeding behaviors at the speed management zone followed a similar trend. Comparing the general trend for trucks and passenger cars (Tables 3 and 4), for the majority of the traffic conditions, time of day, and day of the week, the passenger car and truck drivers showed a similar trend while observing the speed management strategy.

At sites with SFS+E and E (sites 1, 2, 3, 7, 8 and 9), the law enforcement was intermittent. Therefore, the results suggest that the SFS+E and E strategies reduce the overall speed during the study period despite the fact the law enforcement was not always present. This study does not specifically differentiate between active law enforcement and inactive law enforcement but looks at the treatment as a whole strategy over the study period.

At sites 3 and 8 the roadway has a downgrade with an average slope of 3% and 3.3%. The results of the average speed and 85th percentile of the speed showed drivers sped up going from BDC to DDC (potentially due to the downgrade). The speeds increased from the BDC to the later points despite the treatment. We recommend additional studies to isolate the effects of the downgrade from the effects of the speed management strategy since the speeds may be lower than they would have otherwise been.

At site 6 the baseline data were collected right after the spiral of the curve and a side street entrance. Due to these two conditions, the average speed at baseline had dropped significantly. The average speed and 85th percentile of speed increased at the SMDC point relative to the BDC point. No conclusion for the potential impact of the speed management strategy for this location could be made, however, the results are still presented for comparison in studies that may occur by other agencies.

At site 7, the second data collection point (SMDC) was located right after an intersection. To remove the impact of intersection delay on the drivers' speed behavior, only the drivers with speed higher than 40 mph were included in the analysis since it is assumed that they approached the intersection at a green light without impediment from a queue. At this site, the immediate effect was negative, meaning drivers slowed down right after observing speed management. However, it is difficult to say if the signal or the reduction strategies were the reason for the observed differences.

4.3. Comparing the effectiveness of speed management strategies

All the speed management strategies proposed in this study have a positive effect on both passenger car and truck drivers in reducing their average speed and complying with the posted speed limit. However, agencies are looking for the most effective strategy. To compare the effectiveness of these strategies, robust heteroscedastic ANOVA, a revised type of mixed ANOVA was used. Robust statistical methods are innovative methods meant to handle conditions where the assumption of homoscedasticity of data, which is an underlying assumption of ANOVA, is not met. The ANOVA framework used in this study consisted of one dependent variable and two independent variables as described in Table 5.

Consider $J = 1, \cdots, J$ as the between-subject variable, and $k = 1, \cdots, K$ as the within-subject variable. In our case, J = 3 as the total number of speed management strategies (SFS, E, and SFS+E), K = 3 shows the data collection points (BDC, SMDC, and DDC), and the dependent variable is the effectiveness of each speed management strategy. The structure of the statistical hypothesis for a mixed ANOVA consists of three pairs of hypotheses: 1) within-subject hypothesis, 2) between-subject hypothesis and 3) the interaction hypothesis. In order to compensate for the inequality of the variance, 10 percent of the means from both higher and lower tails of the data were trimmed. For this study, the hypotheses are described below:

1- Within-subject hypothesis

Table 5
Dependent and Independent Variables Used in this Study.

Variables	Represents
Dependent Variable (DV)	Average Speed
Independent Variable (IVs)	
Within-subject variables	Type of Data Collection Points: 1. Baseline Data Collection 2. Speed Management Data Collection 3. Downstream Data Collection
Between-subject variables	Type of Speed Management Strategy 1. Speed Feedback Sign + Enforcement (SFS+E) 2. Speed Feedback Sign (SFS) 3. Enforcement (E)

$$\mathrm{H_0}: \mu_{\mathrm{BDC}} = \mu_{\mathrm{SMDC}} \& \mu_{\mathrm{BDC}} = \mu_{\mathrm{DDC}} \& \mu_{\mathrm{DDC}} = \mu_{\mathrm{SMDC}}$$

$$\mathrm{H_a}: \mu_{\mathrm{BDC}} \neq \mu_{\mathrm{SMDC}} \mathrm{OR} \mu_{\mathrm{BDC}} \neq \mu_{\mathrm{DDC}} \mathrm{OR} \mu_{\mathrm{DDC}} \neq \mu_{\mathrm{SMDC}}$$

The null hypothesis ($\mathrm{H_0}$) states that the average speed between each pair of data collection points is equal and the alternative hypothesis ($\mathrm{H_a}$) states that the average speed of one or more pairs of data collection points is not equal.

2- Between-subject hypothesis

$$\mathrm{H_0}: \mu_{\mathrm{SFS+E}} = \mu_{\mathrm{SFS}} \& \mu_{\mathrm{SFS+E}} = \mu_{\mathrm{E}} \& \mu_{\mathrm{SFS}} = \mu_{\mathrm{E}}$$

$$\mathrm{H_a}: \mu_{\mathrm{SFS+E}} \neq \mu_{\mathrm{SFS}} \mathrm{OR} \mu_{\mathrm{SFS+E}} \neq \mu_{\mathrm{E}} \mathrm{OR} \mu_{\mathrm{SFS}} \neq \mu_{\mathrm{E}}$$

The null hypothesis ($\mathrm{H_0}$) states that the average speed between each pair of speed management strategies is equal and the alternative hypothesis ($\mathrm{H_a}$) states that the average speed between one or more pairs of speed management strategies is not equal.

3- Interaction hypothesis

The interaction hypothesis draws a relationship between the interaction of both within-subject and between-subject variables. The null hypothesis states that the average speed between each pair of strategy and data collection point are equal. While the alternative hypothesis states that the average speed between each pair of strategy and data collection point are not equal.

The resulting p-value for the above hypotheses was 0.025, 0.007, and 0.0001 for within-subject effects, between-subject, and interaction effect, respectively. The p-values indicate that at a significance level of 0.05, enough evidence exists to reject the null hypothesis for all three hypotheses above. That is, the average speed is different at each data collection point, and the effectiveness of speed management strategies is different from each other. Although the hypothesis showed that the effectiveness of speed management strategies is different from each other, ANOVA is an omnibus test statistic. That is, it cannot provide information regarding which speed management strategy is more effective. Therefore, in order to rank the effectiveness of the speed management strategies, a pairwise group comparison between every two pairs of between-subject variables is performed. In other words, this test will compute a score for each speed management strategy and compare them together. The value of difference scores for each pair of speed management strategy is computed as below. R-package WRS2 is used to carry out this test (Mair & Wilcox, 2018).

$$\begin{cases} S_{(SFS+E)} - S_{(E)} = 2.4 \\ S_{(SFS+E)} - S_{(SFS)} = 0.6 \\ S_{(E)} - S_{(SFS)} = -1.8 \end{cases}$$

where S is the score for each 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. A positive value for the first two scores indicates that SFS supported with periodic law enforcement is more effective than SFS-only and periodic enforcement-only strategies. A negative value for the last score indicates that SFS-only is more effective than a periodic enforcement-only strategy.

4.4. Spatial halo effect exploration

The results of comparing the effectiveness of speed management strategies showed the speed feedback sign supported with periodic law is the most effective speed strategy. However, one of the major drawback of the fixed-point speed management strategies, such as SFS or speed enforcement cameras, compared to section-based speed management strategies (e.g., Average section speed control) is that drivers only abruptly decelerate their speed in the immediate vicinity of the enforcement strategy, and after passing the enforcement strategy, they will quickly regain their speed. This phenomenon is called the spatial halo effect (De Pauw et al., 2014b; Woo et al., 2007). To analyze this phenomenon carefully, speed data were also collected downstream of the speed management strategy zone (DDC). Three measures, speed difference between the speed collected at the SMDC and the DDC point, the proportion of drivers exceeding the speed limit, and the proportion of drivers exceeding the speed limit by more than 5 mph at the BDC, SMDC, and DDC point, were considered.

Based on these measures, it was observed that for the sites with SFS supported with periodic law enforcement (sites 1 and 2), both the immediate and secondary effects were negative (Tables 3 and 4), meaning 0.3–2.5 mph decrease in driver's speed going from BDC to SMDC, and an additional 2.5–3.5 mph decreases in driver's speed going from SMDC to DDC was observed (the decrease in speed was statistically significant at p = 0.05). In other words, the drivers constantly slowed down even after passing the speed management strategy. For these sites, the spatial effects of the SFS+E were extended to 0.27 miles and 0.22 miles after passing the speed management zone, respectively. This trend could be evidence that by supporting the fixed-point SFS with periodic law enforcement, we can extend the spatial effectiveness distance of fixed-point management strategy.

Similar results were observed for the other two measures. Fig. 6, shows the bar plots for the proportion of drivers going over the speed limit at each data collection point, and the proportion of drivers going five mph over the speed limit. Based on

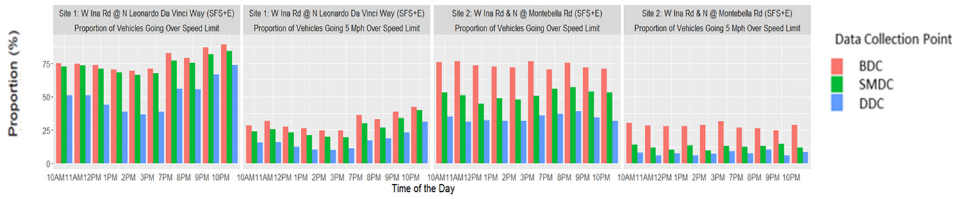

Fig. 6. Effect of different speed management strategies on the proportion of drivers exceeding the speed limit (SFS+E).

this figure, for sites 1 and 2, the proportion of drivers going over the speed limit and going over 5 mph over the speed limit decreased over the data collection points (continuously going from BDC to SMDC and from SMDC to DDC).

For sites with SFS-only or Enforcement-only (sites 4, 5, 7, and 9), although the immediate effect was negative, the secondary effect was positive, an increase of 1.5–4 mph in driver's speed going from SMDC to DDC was observed (the increase in speed was statistically significant at p = 0.05). This means that drivers regained their speed after passing the speed management zone. In other words, the speed management strategy lost its influence on driver behavior in a spatially limited distance. Similar results were observed for the proportion of drivers going over the speed limit and going over 5 mph over the speed limit (Fig. 7).

Based on the above illustration (Figs. 6 and 7) and the results from Tables 3 and 4, the existence of periodic law enforcement could potentially change drivers' behavior and increase the spatial effectiveness of fixed-point speed management strategy. While the results presented are statistically significant for the time period, it is important for the study to be replicated. We believe the evidence is strong enough that agencies should consider implementing SFS supported by periodic law enforcement and share results of their local implementations. Some recommendations are for other agencies interested in doing a similar study include careful selection of geometric features, data collection strategies, and enforcement types.

5. Discussion

The overall effect of the speed management strategies (SFS, E, and SFS+E) showed that all the speed management strategies proposed in this study had a positive effect on drivers in reducing their average speed and complying with the posted speed limit. However, to further evaluate the change in the average speed among various speed management strategies and at different data collection points, a robust heteroscedastic ANOVA was used. Fig. 8 illustrates the interaction plot between the dependent variable (average speed), between-subject variables (speed management strategies), and within-subject variables (data collection points); this plot is only developed for two sites in each category (Sites 1&2 for SFS+E, Sites 4&5 for SFS, and Sites 7&9 for E).

Based on Fig. 8, it can be seen that for all the speed management strategies, going from the BDC to SMDC, drivers tend to slow down. However, going from SMDC to DDC, the only effective strategy is SFS+E.

Furthermore, this study indicated that periodic enforcement boosts the effectiveness of SFSs. DOTs that already have SFS can implement periodic enforcement in locations where the SFS is not fully effective. DOTs looking to expand SFS coverage can consider adding enforcement areas at new locations to facilitate periodic law enforcement at sign locations. In general, coordinated efforts between transportation agencies and law enforcement will help to address speeding.

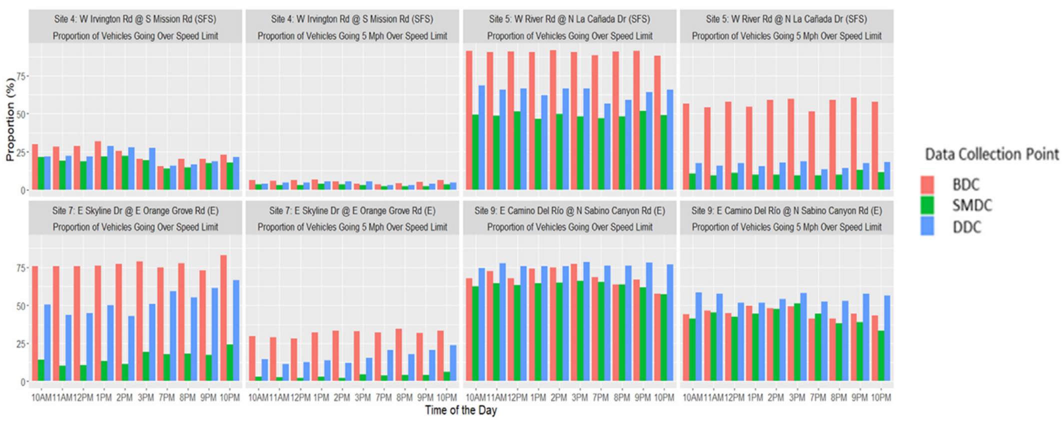

Fig. 7. Effect of different speed management strategies on the proportion of drivers exceeding the speed limit (SFS-only & E-only).

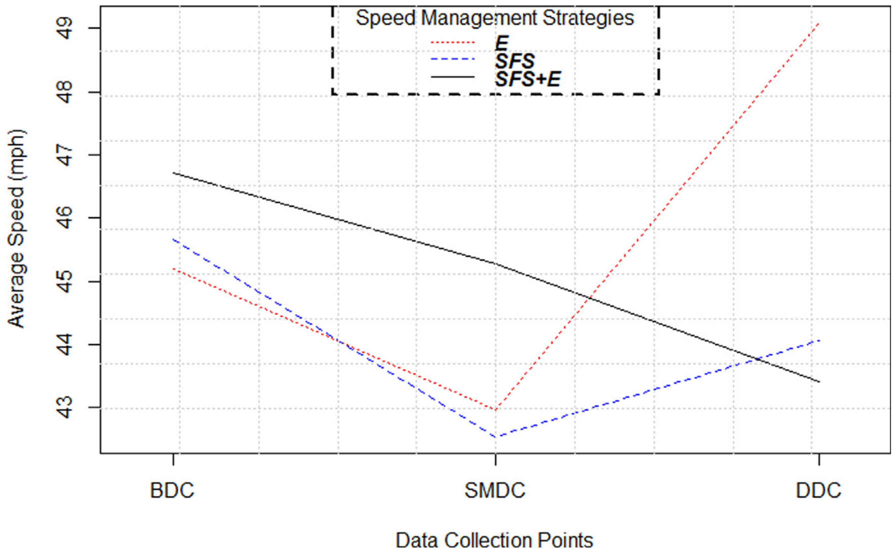

Fig. 8. Interaction plot of the heteroscedastic ANOVA test.

6. Conclusion

This study aimed to analyze the effects of Speed feedback signs (SFS), Periodic law enforcement (E), and Speed feedback signs supported by periodic law enforcement (SFS+E), on driver speed behavior and compliance. In order to evaluate the impact of each strategy, nine sites in Pima County, Arizona were selected. At each study site driver's speed, date, time, vehicle's length, and the number of vehicle axles were collected using paired pneumatic tubes. 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 were a) average speed, b) proportion of drivers exceeding the speed limit, and c) proportion of drivers exceeding the speed limit by more than 5 mph.

The general effect of the speed management strategies (SFS, E, and SFS+E) showed that all the speed management strategies proposed in this study had a positive effect on drivers in reducing their average speed and complying with the posted 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 fixed-point SFS with periodic law enforcement, the distance at which drivers regain their speeds after passing the speed management zone was increased. Similar behavior was observed from both truck and passenger car drivers while approaching the speed management strategy. That is, both truck and passenger car drivers tend to slow down after observing the speed management strategy. Therefore, for agencies looking for a robust and reliable speed management strategy, it is suggested to adopt the approach of speed feedback sign with periodic law enforcement.

Some of the potential limitations of this study are as follow. The first limitation was that the cross-sectional study design resulted in different speed management strategies being evaluated at different locations. While the site selection was carefully thought through to ensure sites were comparable, there were still some nuanced differences at the sites. Additionally, a single-site study design would have had its drawbacks associated with the time required to collect data for each treatment and possible lasting effects between different treatments. While the treatment for enforcement was treated equivalently across sites, we did not determine the most effective approach to enforcement, both in terms of time and level of enforcement (citations vs warnings). In addition, based on the availability and size of police pullout, different enforcement vehicles (full-size vehicles, motorcycles) were utilized for the periodic law enforcement strategy. The third limitation of this study was the short study period. Only the short-term effect of the speed management strategies was reported in this study and the long-term effects of the treatments are still unknown. As locals start to get used to seeing enforcement behind SFS, compliance may improve further and it may affect behaviors at other SFS, however that requires further study. While the limitations discussed here should not have a significant impact on the results of this study, additional research should be conducted to extend the study's findings before widespread implementation. More studies would be needed to comprehensively evaluate if geometric design and topography are intruding on the positive impact of speed management strategy. Future studies could also evaluate whether law enforcement vehicle types impact driver behavior.In addition, adding cost-benefit analysis is critical for comprehensively evaluating the proposed strategies.

CRediT authorship contribution statement

Abolfazl Karimpour: Conceptualization, Methodology, Visualization, Software, Writing - original draft, Writing - review & editing. **Robert Kluger:** Conceptualization, Methodology, Visualization, Writing - review & editing. **Chenhui Liu:** Visualization, Writing - review & editing. **Yao-Jan Wu:** Writing - review & editing, Supervision.

Acknowledgment

The authors would like to thank the Pima County Department of Transportation (PCDOT) for funding and data support and the Pima County Sheriff's Department for handling the enforcement part of this study. Special thanks go to Seth Chalmers, Tobin Bennett-Gold and Stephen Wilson for their support.

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