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A Comprehensive Review of Dynamic Speed Feedback Signs in Reducing Speed at Different Critical Locations

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Review
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ABSTRACT
Excessive speed is one of the main causes of fatal crashes worldwide. One speed reduction measure is dynamic speed feedback signs (DSFS), whose main purpose is to make drivers aware of their excessive speed and thus influence their behaviour in a way that they reduce their driving speed. The objective of this review is to discuss the benefits of implementing DSFS in different settings, identify the most effective placement and messaging strategies, analyse the public perception and temporal effect of DSFS, and identify potential locations where this device can be further deployed. The study includes 44 studies, of which 35 are journal publications, three are conference proceedings and six are technical reports. The identified studies are divided into six categories based on their topic: (1) operational benefits of DSFS; (2) safety benefits of DSFS; (3) public perception of DSFS; (4) position of DSFS installation, message type and triggering; (5) temporal effect of DSFS; and (6) effect of vehicle type. The results of this study provide information on the use of DSFS and as such are valuable to road authorities and researchers.

KEYWORDS
dynamic speed feedback sign; driving speed; driver behaviour; road safety; review.

1. INTRODUCTION

Dynamic speed feedback sign (DSFS) systems are traffic control devices that use speed detection technology such as radar or LiDAR to determine the travel speed of approaching vehicles and display the determined speed in real time on a digital screen. In the literature, they are also referred to as dynamic warning signs, radar speed signs, radar message signs, electronic speed signs and dynamic speed display panels. Their main purpose is to warn motorists of speeding violations and make them feel that they are being monitored, thus influencing their behaviour and driving speed.

Because DSFS provide targeted feedback to the approaching driver, they have been shown to be effective in reducing speed. A meta-analysis of 43 publications conducted by Flynn et al. showed that DSFS reduce speed in all types of settings (work zones, school zones, transition zones, straight sections, horizontal curves, etc.) and vehicle types [1]. Although DSFS are generally effective, their effectiveness is influenced by a number of factors, including setting, sign position, message type, duration of presence at a given location, etc. Therefore, it is critical to understand how and to what extent these factors affect DSFS effectiveness in different settings, all for the purpose of choosing the most appropriate DSFS strategy.

The aim of this study is to present a comprehensive overview of the impacts of DSFS in a variety of situations and to ascertain its optimal utilisation. In contrast to the meta-analysis undertaken by Flynn and colleagues in 2020, which involved quantitatively synthesising data from 43 studies regarding DSFS effectiveness, this paper relies on qualitative analysis and summarisation of existing literature. It aims to explore the advantages of incorporating DSFS in diverse contexts, identify the most effective placement and messaging strategies, analyse the public perception and temporal impact of DSFS, and identify potential locations for deploying this measure. The paper is conceptualised as follows: (1) introduction, (2) methodology, (3) results, (4) discussion and (5) conclusion. The results section is divided into several subsections based on their topic: (1) operational benefits of DSFS; (2) safety benefits of DSFS; (3) public perception of DSFS; (4) position of DSFS installation, message type and triggering; (5) temporal effect of DSFS; and (6) effect of vehicle type.

2. METHODOLOGY

For this review, we used the Web of Science (WoS) as the main database for literature search because it includes several important scientific databases such as Current Contents, Science Citation Index, Science Citation Index Expanded, Scopus and Transportation Research Record. In addition, we also used Google services since some of the studies are professional in nature (reports) and are not included in scientific databases, but still contain valuable findings.

The search included studies published in English between 01/01/1990 and 01/01/2022 in peer-reviewed journals, conference proceedings or technical reports. Because terminology for DSFS varies in the literature, broad search terms were used (dynamic speed feedback signs OR radar speed signs OR radar message signs OR electronic speed signs OR dynamic speed display signs OR dynamic warning signs OR speed monitoring display). The database search, using both WoS and Google, was conducted on 02/14/2022.

The PRISMA method was used for the purpose of this review. The first step of the WoS search yielded 1,416 studies. In the next step, duplicates were removed, bringing the total number to 1,289 studies, which were then screened by at least two members of the research team based on the title and abstract. After this step, 64 studies remained whose full papers were also screened by at least two members of the research team. In reviewing the full papers, the inclusion criterion was that the research related only to DSFS and its effects on drivers and road safety. Potential discrepancies were resolved through discussion between authors. Finally, a total of 38 scientific papers were selected for this review. In addition, six other technical reports were identified, bringing the total number of studies included in this review to 44. The literature selection process is shown in *Figure 1*.

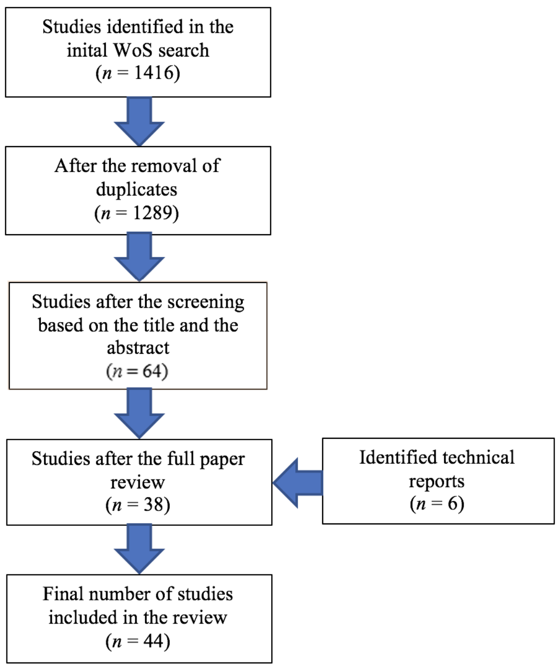

Figure 1 – PRISMA flow diagram of the database search process and identification of the final list of studies

3. RESULTS

Of the 44 studies identified as relevant, 35 were journal publications, three were conference proceedings and six were technical reports. The included studies are categorised by topic as follows: (1) operational benefits of DSFS; (2) safety benefits of DSFS; (3) public perception of DSFS; (4) position of DSFS installation, message type and triggering; (5) temporal effect of DSFS; and (6) effect of vehicle type.

3.1 Operational Benefits of DSFS

As mentioned earlier, DSFS have often been used as a speed reduction measure. However, when considering the operational benefits of DSFS, one must consider the setting, i.e. the traffic situation, in which DSFS are deployed. In general, DSFSs have been utilised across different settings including school zones, residential areas, speed transition zones, high-speed arterials, sharp horizontal curves, freeway exit ramps and work zones on both freeways and rural highways. Therefore, we have divided this section into subsections, each representing a specific application area of DSFS.

DSFS in work zones

In the study of work zone safety, the vast majority of research has focused on speed reduction systems, more specifically DSFS or various types of changeable message signs (CMS) or speed trailers [2].

In 1994, Garber and Patel conducted a study that investigated alterations in travel speed. This research focused on the implementation of four distinct feedback messages at seven work zones situated along two interstate highways in Virginia [3]. The study used radar-activated changeable message signs with a detection range of 300-600 feet that displayed speed-dependent feedback. The DSFSs were placed on 65 mph highways, with the intent to reduce speeds to 45 mph or 55 mph. Among the four types of feedback messages assessed, "YOU ARE SPEEDING SLOW DOWN" proved to be the most impactful, with a significant reduction in the average speed of vehicles travelling at 59 mph or higher. It was followed in effectiveness by "HIGH SPEED SLOW DOWN," "REDUCE SPEED IN WORK ZONE" and "EXCESSIVE SPEED SLOW DOWN." As a result of implementing DSFS, the study recorded a speed reduction, typically ranging from 8 to 10 mph. Additionally, a decrease in the percentage of vehicles exceeding 55 mph, including reductions of 5 mph and 10 mph, was observed. The second phase of the above project examined the effects of work zone length and vehicle types, as well as the temporal effects of the DSFS [4]. Based on the findings from the first phase, DSFS was programmed to display "YOU ARE SPEEDING SLOW DOWN" when the detected speed was above the threshold. Results from three sites showed that DSFS was equally effective during its seven-week deployment. In the middle of the work zone, speeds were reduced by 8 to 10 km/h for both cars and trucks. However, in long work zones, vehicles tended to increase speed toward the end of the work zone, and the authors recommended the use of multiple DSFS in such cases. The study also found no significant differences in speed reduction for cars and trucks.

In 1995, McCoy et al. used work zones situated on an interstate highway in South Dakota, to assess the effectiveness of a 20-inch by 28-inch speed display panel installed in a trailer, accompanied by various additional signs - "WORK ZONE" warning sign, a speed limit advisory sign and a "YOUR SPEED" advisory sign [5]. Two DSFS units were strategically positioned at the edge of the shoulder on both sides of the road and 310 feet upstream of the initial taper. The analysis of speed data before and after implementation revealed an average speed reduction of 4 mph for two-axle vehicles and 5 mph for vehicles with more than two axles. Additionally, there was a decrease, ranging from 20% to 40%, in the number of vehicles that exceeded the speed limit by 10 mph.

In 2001, Pesti and McCoy studied the long-term effectiveness of DSFS within work zones situated on rural interstate highways in Nebraska, necessitating a speed reduction from 75 mph to 55 mph [6]. Three temporary speed trailers were strategically positioned in front of three critical segments. Trailers displayed drivers' speeds using a panel featuring 24-inch LED digits and an overhead sign that indicated "SPEED LIMIT 55". These installations were situated within the 2.7-mile stretches between two separate work zones. The study revealed a significant reduction in the average speed by 3 to 4 mph, a reduction in the 85th percentile speed ranging from 2 to 7 mph, and a substantial increase, ranging from 20% to 40%, in vehicle compliance with speed limits and speed thresholds. These outcomes remained consistent throughout the 5-week observation period. In addition, the effect of speed reduction was found to be higher for passenger vehicles than for other vehicles (heavy vehicles).

The same year, Fontaine and Carlson tested the effectiveness of DSFS and portable rumble strips in work zones on two-lane rural roads with low traffic volumes and high speeds [7]. Data on speed and traffic volume were gathered across three scenarios: (1) in the absence of any traffic control measures within the work zone; (2) when standard traffic control measures were in place within the work zone; and (3) when DSFS and related measures were introduced. The findings suggest that DSFS proved to be more effective than rumble strips in reducing speeds within the advance warning zone. In summary, DSFS achieved an average speed reduction of up to 10 mph, contrasting with speed reductions of 2 mph for cars and 7.2 mph for trucks when portable rumble strips were utilised.

In 2002, a Maine Department of Transportation study examined a radar-activated, trailer-mounted portable speed feedback sign installed in a work zone on Interstate I-95 where speeds had to be reduced from 55 mph to 45 mph [8]. The sign was programmed to alternately display "YOU ARE SPEEDING!!!" and "SPEED LIMIT 45 MPH". Overall, a decrease of 7 mph in the average speed, accompanied by an 11 percent reduction in the count of vehicles surpassing the speed limit was observed.

Wang et al. investigated the potential of fluorescent orange sheeting, innovative message signs ("SLOW DOWN, MY DAD WORKS HERE"), and DSFS for speed reduction in rural highway work zones in Georgia [9]. The DSFS displayed "YOU ARE SPEEDING, SLOW DOWN NOW" for vehicles travelling 5 mph above the 45 mph speed limit prescribed for work zones and "ACTIVE WORK ZONE, REDUCE SPEED" for vehicles travelling less than 50 mph. The reduction in average operating speed was 1 to 3 mph for fluorescent orange sheeting and 0.2 to 1.8 mph for innovative signs. Nonetheless, with the installation of DSFS, there was a consistent decrease in the average speed, by a range of 7 to 8 mph, along with a reduction in speed variability. These effects of DSFS remained stable over the entire three-week implementation period.

In 2006, Sorrell et al. conducted a study to investigate the efficacy of radar-equipped portable changeable message signs in mitigating motorist speed within work zones in South Carolina [10]. The study explored four distinct message sequences, comprising "YOU ARE SPEEDING" followed by "SLOW DOWN," "YOUR SPEED IS ______" followed by "SLOW DOWN," "YOUR SPEED IS ______" followed by "THANKS FOR NOT SPEEDING" or "SLOW DOWN," and "YOU ARE SPEEDING" followed by "MINIMUM FINE $200." Overall, the average speed reduced from 3 to 10 mph, while a comparison of messaging approaches revealed that neither positive feedback nor negative feedback significantly increased the speed reduction. However, the study recommended "YOUR SPEED IS ____ " followed by either "THANKS FOR NOTSPEEDING" or "SLOW DOWN" as a messaging strategy because it indicates drivers' actual speed followed by feedback messages. In the same year, Brewer et al. studied the effectiveness of a speed display trailer, a portable changeable message sign with radar (PCMR), and a speed limit sign with an orange border to reduce speed in work zones on a rural interstate and a U.S. highway within city limits [11]. Both the speed display trailer and PCMRs reduced speed (85th percentile speed) for both cars and trucks between 1 and 4 mph at the beginning of the work zone. In addition, compliance with the posted speed limit improved significantly (up to 61%) when both of the above measures were used. The study's findings led to the conclusion that devices providing real-time information about approaching vehicle speeds possess considerable potential to effectively lower speeds and enhance adherence to speed limits within work zones.

In 2012, Roberts and Smaglik in their study tested changeable message signs with radar (CMSR) within work zones situated on a four-lane divided highway in Arizona [12]. The CMSR system displayed two alternating feedback messages: (1) "YOUR SPEED XX MPH"; (2) "POSSIBLE FINE $XXX". It was observed that the speed-only feedback led to a 2 mph reduction in the 85th percentile speed when compared to the "no sign" condition. However, the combination of speed feedback and fine-related messages performed even more effectively, resulting in a 3 mph reduction in the 85th percentile speed.

In 2017, Zhang and Gambatese assessed the impact of various traffic control strategies on reducing speeds within work zones [13]. The tested measures included: (1) speed limit signs ("speed 50"); (2) “speed 50” sign and portable changeable message sign (PCMS) on trailers; (3) “speed 50” sign and a radar speed display; and (4) “speed 50” sign, PCMS and a radar speed display. The findings indicated that Measures 2 and 3 resulted in higher average speeds when compared to Measure 1 at the conclusion of the taper zone. In contrast, Measure 4 exhibited lower average speeds than those achieved with Measure 1. It's important to note that the precise placement of these measures varied on different days during data collection, which may have influenced the results to some extent. In summary, the authors concluded that the most effective approach for reducing vehicle speeds immediately at the end of the taper was the combination of PCMS and radar speed displays, although this effect might not hold consistent over longer distances within a work zone.

Banerjee et al. tested three work zone speed reduction measures using a driving simulator [14]. A standard work zone setting (advance warning signs and posted speed limits) was used as a control condition. To the aforementioned setting, the authors added three elements: (1) speed photo-enforced signs; (2) DSFS; and (3) speed reduction signs. The study involved testing drivers' speed across four distinct phases as they approached and passed these signs: (1) the initial speed range, covering any distance within 375 feet before reaching the start of the subsequent phase; (2) the visible range which represented the distance at which the sign first became visible to the drivers; (3) the legible range, which signifies the distance at which the sign became readable; and (4) the post-sign range, spanning a distance of 250 feet following each of these measures.

The results indicated a progressive reduction in driving speed by participants as they approached the DSFS sign. This reduction occurred both when the sign became visible and legible, and after they had passed the sign. The cumulative speed reduction, extending from the initial speed range to the point after passing the DSFS sign, amounted to approximately 8 mph. However, it was found that the photo-enforced sign was the most effective in slowing down vehicles. In comparison to the second most effective sign, which was DSFS, the overall reduction in speed achieved by the photo-enforced sign was 5 mph greater.

In a study conducted by Anderson et al. DSFS was deployed on roads with speed limits of 70 mph, within a work zone where the speed limit was 55 mph [15]. The DSFS was installed alongside a stationary work zone speed limit sign and had the capability to display the speed of oncoming vehicles. The study's results revealed that at one specific location, the DSFS successfully achieved a 2 mph reduction in speed.

A summary of the methodological approaches and main findings of studies which investigated the operational benefits of DSFS in work zones is presented in *Table 1*.

DSFS in horizontal curves

DSFS have also demonstrated their potential in enhancing road safety by effectively reducing speeds and crash rates, particularly on horizontal curves. In 2000, Tribbett et al. conducted a study that focused on five dynamic curve warning signs incorporating speed-measuring detection radar [16]. These signs were strategically placed along the interstate within the Sacramento River Canyon, as documented in their 2000 study. The sites along the interstate within the Sacramento River Canyon where DSFS were deployed had curve advisory warning speeds ranging from 50 to 60 mph for downstream traffic and 55 to 65 mph for upstream traffic. The study's findings exhibited inconsistencies, with some sites showing a decrease in average speed, while others displayed no change or even an increase. Furthermore, the results varied among different vehicle types. However, the authors note that one possible reason for the inconsistency could be due to the method of data collection method (the stopwatch method was used for collecting speed data).

Ullman and Rose evaluated two horizontal curve sections on a road with a 55 mph speed limit of 55 km/h and a 20 mph advisory speed [17]. After DSFS installation, the average speed of passenger vehicles decreased by 2.1 to 3.5 mph in the short term. The effects on truck speeds were not comparable. Average speeds increased slightly in one location and decreased slightly in another. However, the percentage of vehi-

Table 1 – Summary of the methodological approaches and main findings of studies which investigated operational benefits of DSFS in work zones

Authors and year; Type of study; Setting	Main variables	Message type	Main results
Garber & Patel (1994); Real road; Before-after study; Work zone;	a) Mean speed b) 85th-percentile speed	a) "YOU ARE SPEEDING SLOW DOWN" b) "HIGH SPEED SLOW DOWN" c) "REDUCE SPEED IN WORK ZONE" d) "EXCESSIVE SPEED SLOW DOWN"	a) Significant reduction in the average speed of vehicles travelling ≥ 59 mph b) Speed reduction of 8 to 10 mph after DSFS installation
Garber & Srinivasan (1998); Real road; Before-after study; Work zone;	a) Mean speed b) 85th-percentile speed c) Speed variances d) Percentages of vehicles speeding	a) "YOU ARE SPEEDING SLOW DOWN"	a) Speeds were reduced by 8-10 mph in the middle of the work zone for both cars and trucks b) In long work zones, vehicles tend to increase speed towards the end of the work zone
McCoy et al., (1995); Real road; Before-after study; Work zone;	a) Mean speeds b) Percentages of vehicles exceeding the advisory speed limit	a) "YOUR SPEED"	a) Average speed of 4 mph for vehicles with two axles and 5 mph for vehicles with more than two axles b) 20 to 40 percent decrease in the number of vehicles exceeding the speed limit by 10 mph
Pesti & McCoy (2001); Real road; Before-after study; Work zone;	a) Mean speed b) Standard deviation c) 85th-percentile speed d) Percentage complying with the speed limit e) Percentage complying with the speed limit plus 8 km/ h f) Percentage complying with the speed limit plus 16 km/h	a) Driver's actual speed with sign "SPEED LIMIT 55"	a) Reduction of average speed by 3 to 4 mph b) Reduction of 85th-percentile speed by 2 to 7 mph c) 20 to 40 percent increase in vehicles obeying speed limits and speed threshold
Fontaine & Carlson (2001); Real road; Before-after study	a) Mean speed b) Percentage complying with the speed limit	a) Driver's actual speed	a) The speed reduction ranged from 3.2 to 14.5 km/h (2 to 9 mph) for passenger cars and between 11.3 and 16.1 km/h (7 to 10 mph) for heavy vehicles. b) Decrease in the number of vehicles exceeding the speed limit by 15 to 20 percent
Thompson (2002); Real road; Before-after study	a) Mean speed b) Percentage complying with the speed limit	a) "YOU ARE SPEEDING!!!" and "SPEED LIMIT 45 MPH"	a) Reduction of the average speed by 7 mph b) Reduction of the number of vehicles exceeding the speed limit by 11 percent
Wang et al. (2003); Real road; Before-after study	a) Mean speed b) Speed variance	a) "YOU ARE SPEEDING, SLOW DOWN NOW" for vehicles travelling 5 mph above the 45 mphspeed limit b) "ACTIVE WORK ZONE, REDUCE SPEED" for vehicles travelling less than 50 mph	a) The average operating speed decreased by 7 to 8 mph, in addition to the reduction in speed deviation b) DSFS effects remained similar during the three-week implementation period
Sorrell et al. (2007); Real road; Before-after study	a) 85th percentile speed b) Mean speed c) Frequency of speeds d) Number of observed vehicles speeding	a) "YOU ARE SPEEDING" followed by "SLOW DOWN" b) "YOUR SPEED IS _" followed by "SLOW DOWN" c) "YOUR SPEED IS _" followed by "THANKS FOR NOT SPEEDING" or "SLOW DOWN" d) "YOU ARE SPEEDING" followed by "MINIMUM FINE $200"	a) The average speed decreased from 6 mph (9.7 km/h) above the speed limit to speeds generally within 2 mph (3.2 km/h) above the speed limit b) The 85th percentile speed decreased to approximately 5 mph (8.0 km/h) over the speed limit c) Compliance with the posted speed limit improved significantly (up to 61%)
Roberts & Smaglik (2012); Real road; Before-after study	a) Mean speed b) Speed medians c) The 85th percentile speed d) Percentage of vehicles that exceeded the speed limit	a) "YOUR SPEED XX MPH," alternating with "POSSIBLE FINE $XXX"	a) Although there was only a minor reduction in average speeds, a significant reduction in the number of high-speed vehicles was recorded, ranging from 25% for the speed feedback message to 50% for the combined speed feedback and fine warnings. b) The speed-only feedback led to a 2 mph reduction in the 85th percentile speed, while the 85th percentile speed was decreased by3 mph when the speed feedback alternated with fine-related feedback. c) Substantial decreases in speeding vehicles.
Zhang & Gambatese (2017); Real road	a) Mean speed b) Difference in mean speed	a) "SLOW FOR WORKERS" b) "WORKERS ON ROAD"	a) The effectiveness of reducing vehicle speeds right at the end of the taper is most pronounced when combining PCMS with radar speed displays, although this effect might not extend uniformly over longer distances within a work zone.
Banerjee et al. (2019); Driving simulator	a) Mean speed	a) "YOUR SPEED IS _"	a) The overall reduction in speed was approximately 8 mph for DSFS
Anderson et al. (2021); Real road; Before-after study	a) Mean speed b) Speed compliance	a) Driver's actual speed	a) Speed reduction by 2 mph b) Passenger cars and semi-trucks most often exceed the speed limit

cles exceeding the posted speed limits decreased significantly at both sites, both in the short and long term. At one site, there was a significant reduction in speeding on curves, with a 26 percent decrease for cars and a 28 percent decrease for trucks. Meanwhile, at another site, there was a shorter-term reduction of 13 percent for cars and 24 percent for trucks.

In 2006, Monsere et al. examined two overhead DSFSs on a horizontal curve on the interstate in a before-and-after study [18]. The overhead sign indicated the highest speed within the detection zone. The message was "SHARP CURVE AHEAD" when the speed was below 50 mph, "YOUR SPEED XX MPH" when the detected speed was between 50 and 70 mph, and "YOUR SPEED IS OVER 70 MPH" when the detected speed was above 70 mph. Even though the feedback was not specific to individual vehicles, this approach still managed to achieve a significant reduction in average speed, with a decrease of 3 mph in one direction and 2 mph in the opposite direction.

In 2015, Hallmark et al. conducted an extensive study to assess the effectiveness of DSFS within horizontal curves situated on two-lane rural road sections [19]. Authors tested a speed display sign that presented the approaching vehicle's speed along with the posted speed limit when the speed exceeded the posted limit by 20 mph, and a curve warning sign that displayed both a curve sign and an alternating message encouraging slower speeds for vehicles exceeding the 50th percentile speed. Overall, a significant reduction in average speed was recorded, amounting to 1.82 mph, 2.57 mph and 1.97 mph at one month, 12 months and 24 months following installation, respectively. Furthermore, the findings indicated a substantial decrease in the percentage of vehicles travelling at speeds exceeding the advisory or posted limits by 5 mph, with reductions of 11.8 percent, 18.6 percent and 19.8 percent at the aforementioned timeframes. The percentage of vehicles exceeding these limits by 10 mph, 15 mph, or 20 mph was even higher.

In 2022, Mahmud et al. assessed the impacts of DSFS on rural highways featuring a 65 mph speed limit, specifically focusing on the sections approaching horizontal curves with advisory speed limits spanning from 25 to 60 mph [20]. The authors focused on two specific locations: 1) the point of the curve (PC); and 2) the location of the curve advisory sign. When DSFS was installed at the PC curve entry speed decreased from 0.1 to 2.8 mph. Speed reduction was between 0.7 to 3.5 mph when DSFS was placed at the curve advisory speed sign location. Additionally, the authors recorded a significant 25% to 40% decrease in the number of vehicles exceeding the advisory curve speed by 10 mph. As a final recommendation, the authors suggested deploying DSFS upstream of the PC, particularly in locations where the difference between the upstream speed and curve advisory speed exceeds 25 mph or more.

Montella et al. conducted a driving simulator study and tested several measures of which one included DSFS with "YOUR SPEED XX" [21]. Overall, DSFS reduced the driving speed at the beginning of the curve from 55 mph to 51 mph.

A summary of the methodological approaches and main findings of studies which investigated the operational benefits of DSFS in horizontal curves is presented in *Table 2*.

DSFS in speed transition zones

Speed transition zones, i.e. zones where varying upstream speeds transition to reduced speed limits, are also settings where DSFS have been utilised as a speed reduction measure. In 2005, Ullman and Rose assessed two such zones in which the speed limit was lowered from 55 mph to 45 mph [17]. Following the installation of DSFS, there was an immediate reduction in average speeds by 3.4 mph and 2.6 mph in the short term, and a 1.4 mph reduction in the long term, at both sites.

Sandberg et al. studied the long-term impacts of DSFS within seven speed transition zones along two-lane rural highways in Minnesota on which speed transitioned from 45-55 mph to 30-45 mph [22]. Overall, the results indicated significant reductions in average speeds, particularly at sites with a greater speed difference. Across all sites studied, the 85th percentile speeds decreased by 7.0 mph, 7.5 mph, 6.3 mph and 6.8 mph at one week, two months, seven months and 12 months after installation, respectively.

In 2009, Cruzado and Donnell conducted a study encompassing a total of 12 speed transition zones on

Table 2 – Summary of the methodological approaches and main findings of studies which investigated the operational benefits of DSFS in horizontal curves

Authors and year; Type of study	Main variables	Message type	Main results
Tribbett et al. (2000); Real road; Before-after study	a) Mean speed b) Changes in speed c) Lane line encroachments d) Brake light actuation e) Crash rate f) Public perception	a) "50 MPH CURVE AHEAD" b) "50 MPH CURVES" c) "YOUR SPEED AHEAD 70 MPH"	a) The results varied by site - at some sites the average speed decreased, while at others it remained unchanged or increased b) Results were also inconsistent for different types of vehicles c) The study noted a general reduction in crashes involving trucks but presented mixed findings regarding passenger vehicle crashes; however, the study was unable to draw conclusions due to limited data on crashes during the follow-up period d) On average, 80% of drivers considered the information conveyed by DSFS to be valuable
Ullman & Rose (2005); Real road; Before-after study	a) Mean speed b) The 85th percentile speed c) Percentage of vehicles that exceeded the speed limit	a) "YOUR SPEED IS _"	a) The average speed of passenger cars decreased by 2.1 to 3.5 mph in the short term, while the effect on the speed of trucks was not comparable b) Significant reduction in the proportion of vehicles exceeding the posted speed limits, both in short and long-term
Monsere et al. (2005); Real road; Before-after study	a) Mean speed b) Changes in speed distribution	a) "SHARP CURVE AHEAD" if the speed was below 50 mph b) "YOUR SPEED XX MPH" if the detected speed was between 50 and 70 mph c) "YOUR SPEED IS OVER 70 MPH" if the detected speed was above 70 mph	a) The average speed was reduced by 3 mph in one direction and 2 mph in the other direction b) The speed distributions of cars and trucks exhibited statistically significant differences c) Only a minor proportion of vehicles were observed to be travelling at speeds exceeding 70 mph while the DSFS was operational
Hallmark et al. (2015); Real road; Before-after study	a) Mean speed b) Speed compliance c) Crash data	a) "YOUR SPEED XX" for drivers travelling over the 50th percentile speed up to 20 mph over the posted speed limit b) "SPEED LIMIT XX" for drivers travelling 20 or more mph over the speed limit c) Curve warning sign showing a curve sign and an alternating slowdownmessage to the vehicles exceeding 50th percentile speed	a) Significant reduction in average speed of 1.82 mph, 2.57 mph and 1.97 mph at 1 month, 12 months and 24 months after installation, respectively b) Significant reduction in the percentage of vehicles travelling at speeds exceeding the advisory or posted speed limits by 5 mph, with decreases of 11.8 percent, 18.6 percent and 19.8 percent at 1 month, 12 months and 24 months, respectively. c) The percentage of vehicles exceeding the advisory or posted speed limit by 10 mph, 15 mph, or 20 mph decreased by even greater amounts d) Overall, there was a 5 to 7 percent decrease in the number of crashes during the first three years following the installation of DSFS.
Montella et al. (2015); Driving simulator	a) Mean speed b) Deceleration rate	a) "YOUR SPEED XX"	a) DSFS reduced the driving speed at the beginning of the curve from 55 mph to 51 mph
Mahmud et al. (2022); Real road; Before-after study	a) Mean speed b) The percent change between the fraction of vehicles exceeding the posted or advisory speed	a) "YOUR SPEED XX" b) "YOUR SPEED XX" with alternating "SLOW DOWN" message	a) DSFS significantly decreased the proportion of vehicles entering the curve at speeds 5 or 10 mph above the curve advisory speeds b) At the curve entry, speed reduced between 0.1 to 2.8 mph when DSFS was installed at the PC, and between 0.7 to 3.5 mph when it was placed at the curve advisory speed sign c) The number of vehicles exceeding the curve advisory speed by 10 mph was reduced by 25 to 40 percent d) Presence of DSFS also reduced the likelihood of speeding (78.8 to 92.4 percent reduction)

Table 3 – Summary of the methodological approaches and main findings of studies which investigated operational benefits of DSFS in speed transition zones

Authors and year; Type of study	Main variables	Message type	Main results
Ullman & Rose (2005); Real road; Before-after study	a) Mean speed b) The 85th percentile speed c) Percentage of vehicles that exceeded the speed limit	a) "YOUR SPEED IS _"	a) In the short term, the average speed was reduced by 3.4 mph and 2.6 mph, and in the long term by 1.4 mph b) Drivers who exceeded the posted speed limit significantly reduced their speed compared to those who adhered to the speed limits
Mahmud et al. (2022); Real road; Before-after study	a) Mean speed b) The percent change between the fraction of vehicles exceeding the posted or advisory speed	a) "YOUR SPEED XX" b) "YOUR SPEED XX" with alternating "SLOW DOWN" message	a) The most substantial speed reduction was observed at the DSFS site - 3.2 to 7.8 mph reduction when the sign was active b) At the reduced speed limit sign, the speed reduction ranged from 3.6 to 6.2 mph c) In the presence of the DSFS the likelihood of speeding decreases significantly - 78.8 to 92.4 percent reduction
Sandburg et al. (2009); Real road; Before-after study	a) Mean speed b) 50th (median), 85th and 95th percentile speeds c) 10-mph Pace	a) "YOUR SPEED XX"	a) Significant decrease in mean and 50-, 85- and 95-percentile speeds, especially at the sites with higher speed differences at the transition zone b) 85th percentile speeds decreased by 7.0 mph, 7.5 mph, 6.3 mph and 6.8 mph after 1 week, 2 months, 7 months and 12 months of installation, respectively c) The greatest speed reduction was recorded at higher speeds - 95th percentile - up to 9 mph d) Speed decreased by 10 mph from an initial 41-50 mph to 31-40 mph within the first week and to 31-40 mph at one year with essentially the same percentage of vehicles
Cruzado & Donnell (2009); Real road; Before-after study	a) Mean speed	a) Driver's actual speed	a) The average speed reduction for free-flowing passenger cars was approximately 6.3 mph (10.1 km/h), ranging from 0.8 to11.9 mph (1.3 to 19.2 km/h) b) The effectiveness of the DSFS persisted while the DSFS was active, but diminished once it was removed
Hallmark et al. (2015); Real road; Before-after study	a) Speeds while traversing through the transition zone b) Probability of a vehicle exceeding the posted speed limit at the start of the reduced speed limit zone	a) Driver's actual speed	a) Simple speed feedback sign - Average speeds decreased by 5 to 8 mph and 85th percentile speeds decreased by 3 to 9 mph - The percentage of vehicles exceeding the speed limit by 5 mph or moredecreased from 12 to 62%, by 10 mph or more from 25 to 73%, and by 15 mph or more from 38 to 79% b) A single sign with alphanumeric capabilities - The average speed decreased by 5 mph and the 85th percentile speed decreased by 7 mph - The percentage of vehicles exceeding the posted speed limit by 5, 10, and 15 mph or more mph decreased by 76, 91 and 92 percent, respectively c) Standard speed limit sign with LED lights activated when a driver is going 5 mph or more mph over the posted speed limit - Inconsistent results - Average speed dropped between 0.5 and 5 mph and 85 percentile speed droppedbetween 1 and 6 mph - The percentage of vehicles exceeding the posted speed limit by 5, 10, or 15 mph or more decreased between 10 and 25 percent, 11 and 40 percent and 50 percent, respectively

two-lane rural highways in Pennsylvania, with the aim of assessing the effectiveness of DSFS in lowering speeds as vehicles entered rural communities [23]. The speed limits at the study sites transitioned from 45-55 mph to 25-40 mph. Similar to the previous study, the average speed of passenger cars in free-flowing conditions within the transition zones decreased by 6.3 mph after the installation of DSFS. The effectiveness of DSFS persisted while the DSFS were activated but diminished once they were removed.

Furthermore, Hallmark et al. tested various DSFS types installed at transition zones in three small rural communities in Iowa [24]. A simple feedback sign that solely displayed vehicle speed managed to reduce speeds by an average of 8 mph. Additionally, the number of vehicles travelling at speeds 5 mph over the speed limit decreased by 45% after one month. The second setup featured a static "YOUR SPEED" sign paired with a separate display showing driving speed, resulting in a 5 mph decrease in average speed one month after installation. Another DSFS was capable of displaying alphanumeric messages and showed vehicle speed when the approach speed ranged from 26 to 39 mph, switching to "Slow Down 25" when the approach speed ranged from 40 mph to 75 mph. This setup led to a 5 mph reduction in average speed, along with a 76% decrease in the number of vehicles exceeding the speed limit by 5 mph. On the other hand, DSFS equipped with a speed limit sign incorporating LED lights on its exterior yielded varying results – at one location, the average speed decreased by a mere 0.4 mph, while at another location, the average speed decreased by 6 mph after installation.

In 2022, Mahmud et al. positioned DSFS in advance of the reduced speed limit sign and programmed it to alternate between displaying the speed of approaching vehicles and the reduced speed limit information [25]. The authors highlighted that the most significant speed reduction occurred at the DSFS location, with speeds being 3.2 to 7.8 mph lower when DSFS was operational. At the location of the reduced speed limit sign, speed reductions ranged from 3.6 to 6.2 mph. It was also found that the probability of speeding was 78.8 to 92.4 percent lower when the DSFS was present.

A summary of the methodological approaches and main findings of studies which investigated the operational benefits of DSFS in speed transition zones is presented in *Table 3*.

Freeway exit ramp

More recently, DSFS has also been used at freeway exit ramps to help motorists reduce their speed when transitioning from a high-speed freeway to a low-speed exit ramp. In 2020, Gates et al. undertook a field study to investigate how the use of DSFS influenced the speed choices and braking behaviours of drivers as they approached and entered the curve of a freeway ramp. To achieve this, they employed a yellow "YOUR SPEED" sign equipped with radar technology, along with a speed feedback panel which displayed either the vehicle's current speed or a "SLOW DOWN" message. The primary objective was to assess various strategies for providing feedback to drivers and to determine the most effective sign placement relative to the curve at the freeway on-ramp. A total of ten test conditions were designed: (1) Base condition – without the DSFS; (2) The DSFS positioned at the curve with speed feedback only; (3) The DSFS located at the curve, providing speed information with an intermittent "SLOW DOWN" message when the speed exceeded 40 mph; (4) The DSFS placed at the curve, displaying speed information with an intermittent "SLOW DOWN" message when the speed exceeded 40 mph, alongside an advisory speed panel; (5) The DSFS placed 255 feet upstream of the curve, displaying speed information with an intermittent "SLOW DOWN" message when the speed exceeded 40 mph, in combination with an advisory speed panel; (6) The DSFS positioned 255 feet upstream of the curve, displaying speed information with an intermittent "SLOW DOWN" message when the speed exceeded 40 mph; (7) The DSFS placed 255 feet upstream of the curve, displaying speed information feedback only; (8) The DSFS located 450 feet upstream of the curve, displaying speed information feedback with an advisory speed panel integrated into the pre-existing "EXIT 30 MPH" sign; (9) The DSFS positioned 450 feet upstream of the curve, displaying speed information with an intermittent "SLOW DOWN" message when the speed exceeded 40 mph, in conjunction with an advisory speed panel integrated into the existing "EXIT 30 MPH" sign; and (10) The condition of the site as it existed after the completion of all data collection, with the DSFS fully implemented.

Overall, the findings consistently demonstrate that the implementation of the DSFS led to a reduction in speed when entering the curve and an enhancement in braking performance across all testing scenarios. This improvement was particularly notable among heavy trucks when compared to the control condition (no DSFS). Notably, the most significant enhancements in driver behaviour occurred when the DSFS was positioned 255 feet ahead of the curve and employed a feedback message that alternated between displaying the current speed and urging drivers to "SLOW DOWN" if they were exceeding the curve's advisory speed by more than 10 mph. Interestingly, the inclusion of an advisory speed panel alongside the DSFS did not yield a substantial impact on driver behaviour.

The extension of the above study was published in 2021 to test the effectiveness of DSFS at different sign locations (at the point of curvature versus 350 ft upstream), interchange types (system versus service), times of day (rush hour versus off-peak), lighting conditions (daylight versus dark) and vehicle types (cars versus trucks) [26]. A series of field studies (before–after study) was conducted in which DSFS displayed the speed of all approaching vehicles, alternating with the message “SLOW DOWN” for vehicles approaching at more than 40 mph. The authors concluded that, compared with the control condition (no DSFS), DSFS reduced curve entry speeds and improved braking performance. Overall, the most pronounced impact was observed when the DSFS was located at the curve itself, leading to a decrease in curve entry speeds by approximately 2 mph. Results were consistent for all vehicle types, for both system interchanges and service interchanges. When examining the time of day, DSFS had the most significant impact on reducing curve entry speeds during off-peak hours. This reduction amounted to 0.9 mph, which is almost double the reduction observed during peak hours (0.5 mph) and three times the reduction recorded during off-peak hours (0.3 mph). As in the previous study, the DSFS did not yield a significant impact on drivers' behaviour when placed 350 ft upstream of the point of curvature.

A summary of the methodological approaches and main findings of studies which investigated the operational benefits of DSFS at freeway exit ramps is presented in *Table 4*.

DSFS on arterials

Arterials are another setting in which DSFS have been used to reduce driving speed. In a study conducted by Ullman and Rose in 2005, two roadways with speed limits of 55 mph and 45 mph, located before signalised intersections, were investigated [17]. The results showed that, on average, speed decreased by 3.4 to 3.6 mph in the short term. However, in the long term, the impact of speed reduction varied: in one location, average speed eventually reverted to its previous levels, while in another location, it remained 4.0 mph lower than before. In 2008, Walter and Broughton conducted a study involving ten sites on two-way single-carriageway roads with a 30 mph speed limit [27]. These sites were selected because they lacked traffic calming measures, speed cameras, red light cameras, major intersections, sharp curves and few or no nearby crosswalks. Overall, a significant reduction in the average free-flow speed by 1.4 mph and a 12% decrease in speeding violations when DSFS were initially deployed was recorded. However, once the DSFS were removed from these sites, speeds returned to their previous levels.

Ardeshiri and Jeihani's 2014 study evaluated the short-term and long-term effects of DSFS on arterial roads with speed limits of 25 mph, 35 mph and 45 mph. The research revealed a 5 percent increase in compliance with speed limits and a reduction in speed by 40 percent of the time. However, it also indicated that drivers tended to increase their speed after passing the DSFS, and the effectiveness of DSFS diminished over time. Therefore, authors recommend implementing DSFS primarily at critical locations such as areas with high crash rates, school zones and work zones, supplemented by periodic speed enforcement.

In another study, Krimpour et al. installed four DSFS along the corridor on major signalised arterials in Arizona with a 45 mph speed limit to assess their impact at both the link and intersection levels [28]. The findings did not show a significant difference in signal performance, but there was a notable decrease in the average speed (approximately 1 mph) at three of the four links following DSFS installation. Karimpour et al. also investigated the combination of DSFS and law enforcement on nine arterials with speed limits ranging

Table 4 – Summary of the methodological approaches and main findings of studies which investigated operational benefits of DSFS at freeway exit ramps

Authors and year; Type of study	Main variables	Message type	Main results
Gates et al. (2020); Real road; Before-after study	a) Speed at the point of curvature (curve entry) b) Probability of initial brake response occurringbetween 200 and 600 ft upstream of the PC c) Probability of a vehicle entering the curve below 45 mph	a) "YOUR SPEED XX" b) "YOUR SPEED XX" alternated with the "SLOW DOWN" message when >40 mph and the advisory speed panel	a) In general, curve entry speeds were lower across all DSFS test conditions and vehicle types b) A strong correlation was recorded between vehicle speed measured 1,000 ft before the curve and speed at the point of curvature for all speed models c) Placing DSFS 255 ft upstream of the curve, decreased curve entry speeds by 0.54 to 1.47 mph d) Placing DSFS directly at the point of curvature, decreased curve entry speeds by 0.68 to 1.08 mph e) Installing the DSFS at the location farthest upstream of the curve (450 ft) had no significant effect on curve entry speeds f) The most significant impact on curve entry speeds was recorded when DSFS displayed the speed number combined with an alternating "SLOW DOWN" message for vehicles travelling 10 mph above the advisory speed g) Removing the "SLOW DOWN" message and leaving only the speed digits as feedback, resulted in a significant degradation in speed reduction h) Speed reductions for passenger cars at the curve entry generally ranged from 0.5 to 1.5 mph, while for trucks and buses, curve entry speeds were, on average, 1.54 mph lower; speeds for tractor-trailers were substantially lower, with a reduction of 5.07 mph when the DSFS was operational at the location
Mahmud et al. (2021); Real road; Before-after study	a) Mean speed b) Probability of initial brake response occurring between 200 and 600 ft upstream of the point of curvature c) Probability of a vehicle entering the curve within 15 mph of the advisory speed	a) "YOUR SPEED XX" b) "YOUR SPEED XX" alternated with the "SLOW DOWN" message when >40 mph and the advisory speed panel	a) Curve entry speeds were reduced by approximately 2.0 to 2.3 mph when the DSFS was positioned directly at the point of curvature b) When positioned at the point of curvature, DSFS also decreased the occurrence of drivers entering the curve at speeds exceeding the curve's advisory speed - they were 1.7 to 2.5 times more likely to enter the curve at a speed below 15 mph, which is in line with the curve advisory speed c) The DSFS demonstrated an enhancement in braking performance when placed at the point of curvature; drivers were 1.4 to 1.8 times more likely to initiate braking between 200 and 600 ft upstream of the curve when the DSFS was in place d) The DSFS had its most substantial impact on reducing speed at the entrance to the curve during off-peak hours of the day; this reduction amounted to 0.9 mph, which is nearly double the reduction observed during peak hours (0.5 mph) and three times that recorded during nighttime hours (0.3 mph). e) The DSFS elicited a similar response from drivers across all vehicle categories

Table 5 – Summary of the methodological approaches and main findings of studies which investigated the operational benefits of DSFS on arterials

Authors and year	Type of study/Setting	Variables/Message type	Main results
Ullman & Rose (2005); Real road; Before-after study	a) Mean speed b) The 85th percentile speed c) Percentage of vehicles that exceeded the speed limit	a) "YOUR SPEED IS _"	a) Average speed reduced by 3.4 to 3.6 mph in the short-term b) In the long-term, the effect of speed reduction exhibited inconsistency - at one site, the average speed eventually reverted to its previous conditions, while at another site, it remained 4.0 mph lower than before
City of Bellevue Transportation Department (2009); Real road	a) The 85th percentile speed	a) "YOUR SPEED XX"	a) The reduction in 85th percentile speed ranged from 2.0 to 6.3 mph b) Significant speed reduction was observed over multiple years of observation
Ardeshiri & Jeihani (2014); Real road; Before-after study	a) Mean speed b) Compliance with the speed limit	a) Driver's actual speed	a) The mean speeds before- and- after indicated that the DSDS is an effective short term tool for short-distances b) Changes in speed limit compliance due to DSDS, upstream speed limit compliance, time of day and day of week
Karimpour, Kluger, & Wu (2021); Real road; Before-after study	a) Number of vehicles arriving at an intersection, aggregated every 15-min by each approach b) The percentage of vehicles that arrived at the intersection when the signal was red c) Total amount of time that all vehicles spend in the intersection queue while waiting to pass the intersection d) The occurrence of left-over demand for a specific approach at an intersection e) The average vehicle operating speed on each roadway links	a) "YOUR SPEED XX" alternated with the "SLOW DOWN" message when driving speed is above 10 mph of the posted limit	a) No significant impact of DSFS on measures of signal performance was observed b) Link speed before and after DSFS deactivation had a similar peak value; however, average speeds were higher before DSFS than after DSFS c) The influence of DSFS on driver behaviour is contingent on their approach speed; drivers within specific speed categories exhibit different behaviours upon receiving speed information from DSFS d) The financial benefits per year linked to the reduction in severe crashes on the studied arterials equipped with active DSFS indicated encouraging safety enhancements
Karimpour et al. (2021); Real road; Before-after study	a) Mean speed b) Probability of not obeying the speed limit c) Probability of going 5 mph over speed limit	a) "YOUR SPEED XX"	a) DSFS alone led to a reduction in average speeds ranging from 0.8 mph to 5.8 mph; at a site with a higher speed limit (50 mph), average speeds increased at the DSFS location b) When DSFS was complemented with periodic law enforcement, travel speeds at DSFS sites decreased by 0.3 to 2.5 mph c) The presence of enforcement resulted in an extra reduction of 2.5 mph to 3.5 mph beyond the location of the DSFS

from 40 to 50 mph [29]. The results demonstrated that DSFS alone reduced average speeds by 0.8 mph to 5.8 mph at two locations. At one location, which had a higher speed limit (50 mph), the average speed increased after the installation of DSFS. However, when DSFS was complemented with periodic law enforcement, the reduction in average speed extended beyond the location of the DSFS. The presence of enforcement resulted in a decrease ranging from 0.3 mph to 2.5 mph at the DSFS site as well as a decrease from 2.5 mph to 3.5 mph beyond that point.

A summary of the methodological approaches and main findings of studies which investigated the operational benefits of DSFS on arterials is presented in *Table 5*.

DSFS in school zones and residential neighbourhoods

DSFS are commonly employed in school zones to enforce lower speed limits during school arrival and dismissal times and as a component of traffic calming measures in neighbourhoods.

As part of their broad study, Ullman and Rose examined the effectiveness of DSFS installed in advance of three school zones with speed limits ranging from 35 mph to 45 mph [17]. Their research revealed a short-term average speed reduction of 9.2 mph and a long-term speed reduction of 8.8 mph following the installation of DSFS. Additionally, the study observed a decrease in the number of drivers exceeding the speed limit - from 95% to 34% (short-term) and 44% (long-term). Interestingly, the authors also noted a small yet significant decrease in speeds even during periods when the school zone and DSFS were not active. This led the authors to suggest that the part-time operation of DSFS might have a positive carryover effect on driver behaviour.

In 2012, O'Brien and Simpson installed DSFS which included signs displaying "SCHOOL," the speed limit, school hours, and a "YOUR SPEED" sign, in school zones in North Carolina [30]. After the installation of DSFS, speed was reduced on average by 3 to 4.5 mph on all locations over one year following installation.

Furthermore, one study examined the long-term impact of DSFS in a university environment and found that 85.6 percent of drivers reduced their speed after the installation of DSFS. Even after one year, the percentage remained high at 80%, indicating the sustained long-term effectiveness of the sign [31].

Bloch's study evaluated DSFS at three locations in Riverside, California, along two-lane residential roads with a 25 mph speed limit [32]. On average, speed was reduced by 6.1 mph at the DSFS location. Furthermore, when the enforcement was present speed reduction was on average 5.9 mph. On the other hand, speed reduction was lower (on average 2.9 mph) when enforcement was not present. A week after the DSFS was removed, speed was reduced on average 0.6 mph at the former DSFS location and 1.7 mph downstream in case when no enforcement was present. In case when enforcement was present, a 0.6 mph average speed reduction was recorded both at the DSFS location and downstream a week after DSFS removal.

The City of Bellevue's Transportation Department conducted a large study which included 20 residential streets with a 25 mph speed limit [33]. Overall, the results demonstrated a significant reduction in 85th percentile speeds, ranging from 0.3 to 6.8 mph, over multiple years of observations, spanning from 1 to 7 years.

Another study tested three different DSFS messaging strategies: (1) DSFS that displayed the driver's speed; (2) DSFS that showed the driver's speeds highlighted in red or green depending on whether they were adhering to or exceeding the speed limit; (3) a verbal coloured DSFS that displayed a "THANK YOU" message in green font if the speed was within the limit or "SLOW" in red font if the driver exceeded the speed limit [34]. The research took place on a residential road with a speed limit of 18.6 mph (30 km/h). Overall, the highest speed reduction was recorded for the verbal DSFS, followed by displaying the speed in red or green, and lastly, displaying only the speed. Additionally, the results suggested that personalised speed feedback impacted the driver's behaviour more compared to standard DSFS.

Churchill and Mishra also tested DSFS on residential roads and observed a significant decrease in average speed during operation, ranging from 1.6 to 5.6 mph, as well as a decrease in the percentage of vehicles exceeding the speed limit [35]. When DSFS were permanently installed on roads with an 18.6 mph (30 km/h) speed limit, the percentage of vehicles triggering the sign significantly decreased. It has to be noted that the triggering threshold was set to 21.8 mph (35 km/h). Furthermore, when a lower threshold was used, the sign was more effective in reducing the average speed. However, the outcomes of the long-term assessment of the sign's impact were inconclusive. Similar results were found by Chang et al. also in residential neighbourhood settings [36]. However, since at one site (the site with the lowest average speed prior to DSFS installation), speed increased by 0.5 mph after the installation of DSFS, authors highlighted that DSFS are more effective at locations with more pronounced speed-related issues.

A summary of the methodological approaches and main findings of studies which investigated the operational benefits of DSFS in school zones and residential neighbourhoods is presented in *Table 6*.

3.2 Safety benefits of DSFS

Only a few studies explored the safety benefits of DSFS, which could be attributed to the limited number of locations used to assess the operational effectiveness of DSFS across various settings. Moreover, in many instances, DSFS have been primarily installed to achieve short-term reductions in speed. Nevertheless, despite the limited number of studies investigating the safety impact of DSFS, these studies have revealed significant reductions in crashes. For instance, a study conducted in 2000 by Tribbett et al. examined the safety outcomes following the installation of five dynamic curve warning signs and found a decrease in truck-related crashes but yielded mixed results for passenger vehicle crashes [16]. However, due to a shortage of post-installation crash data, authors were unable to draw a definitive conclusion.

Hallmark et al. employed two distinct DSFS systems on 22 sites and compared them with 37 control sites which did not have DSFS [24]. The authors used a Bayesian modelling approach to develop crash modification factors and found a reduction in crashes by 5 to 7 percent during the initial three years following the installation of DSFS.

Wu et al. published two studies based on data collected in the city of Edmonton, Canada. Both studies included a large sample of urban road segments and used an empirical Bayesian method for analysis. In the first study, after the installation of DSFS, crashes decreased from 32.5% to 44.9%, with the most substantial reduction occurring in severe crashes associated with excessive speed [37]. The total number of crashes decreased by 36.1 percent, with a 38.0 percent reduction in rear-end crashes, a 32.5 percent reduction in improper lane change crashes and a 38.2 percent reduction in speed-related crashes.

An extensive economic assessment, employing three distinct methods – direct costs, human capital and willingness to pay – demonstrated that the benefit-to-cost ratio of DSFS installation varied significantly. For a two-year service life, this ratio ranged from 8.16 to 20.19, and for a five-year service life, it ranged from 19.84 to 49.06. The second study estimated that the number of collisions decreased by 31.02% on collector sections equipped with DSFS only and by 41.61% on sections treated with both DSFS and mobile photo enforcement. Collector sections treated with both DSFS and mobile photo enforcement showed an 87.62% reduction, however, the authors emphasised that these results cannot be considered conclusive due to the small sample size [38].

Finally, a meta-analysis conducted by Flynn et al. found that speed reductions achieved through the implementation of DSFS (4 mph reduction for passenger vehicles), could reduce pedestrian fatalities by up to 40% [1].

3.3 Public Perception of the DSFS

The way drivers perceive and accept DSFS can also influence their driving behaviour. Several studies that gathered public feedback on DSFS have consistently reported positive responses. For example, in a California survey, an average of 80.0% of drivers found the information provided by DSFS to be useful [16]. Similarly, a questionnaire survey among students at Morgan State University revealed that the majority of respondents would adjust their speed to match the speed limit when encountering a DSFS [39]. Furthermore,

Table 6 – Summary of the methodological approaches and main findings of studies which investigated operational benefits of DSFS in school zones and residential neighbourhoods

Authors and year	Type of study/Setting	Variables/Message type	Main results
Ullman & Rose (2005); Real road; Before-after study; School zones	a) Mean speed b) The 85th percentile speed c) Percentage of vehicles that exceeded the speed limit	a) "YOUR SPEED IS _"	a) In the short term, 9.2 mph decrease in the average speed was recorded, which reduced to 8.8 mph in the long term b) The percentage of drivers exceeding the speed limit decreased from 95 percent to 34 percent in the short term and 44 percent in the long term. c) When the school zone and DSFS were not operational, a small but significant decrease in speed was recorded
O'Brien & Simpson (2012); Real road; Before-after study; School zones	a) Mean speed b) The 85th percentile speed c) The percentage of vehicles exceeding the speed limit d) Standard deviation and pace speed	a) "YOUR SPEED XX"	a) The average speed was 3.8 mph lower 12 months after the installation of the signs b) No equivalent, consistent, and sustained reduction in vehicle speeds was observed outside of school hours, when the sign was deactivated, as during school hours c) Different vehicle speeds depending on the direction of travel outside school hours d) If the direction of travel is not considered, the average speed outside of school hours increased slightly (0.45 mph) one year after the signs were installed
Williamson et al. (2016); Real road; Before-after study; School zones	a) The 85th percentile and mean speeds exceeding the posted speed limit by 5 mph b) The 85th percentile and mean speeds exceeding the posted speed limit by 3 mph	a) "YOUR SPEED XX"	a) 85.6% of drivers who exceeded the speed limit reduced their speed after DSFS installation b) One year later, after the installation of DSFS, 80.0% of drivers who exceeded the speed limit reduced their speed c) The decrease in vehicle speed ranged from 0 to 13 mph (depending on the study group)
Bloch (1998); Real road; Before-after study; Residential neighbourhoods	a) Mean speed b) Percentage of vehicles travelling≥ 16 km/h over the speed limit	a) "YOUR SPEED XX"	a) The speed at the DSFS location decreased by an average of 6.1 mph, while downstream of the DSFS, speed reductions were 2.9 mph without enforcement and 5.9 mph with enforcement b) A week after the DSFS was removed, speed reductions of 0.6 mph were recorded at the former location of the sign and 1.7 mph downstream when there was no enforcement; when enforcement was present, speed reductions of 0.6 mph were observed one week after the removal of signs on both locations (DSFS location and downstream of DSFS)
Chang et al. (2005); Real road; Residential neighbourhoods	a) Mean speed b) The 85th percentile speed	a) "YOUR SPEED XX"	a) Significant decrease in speed at three out of the four sites, ranging from 1.2 to 2.2 mph; At one site, speed increased by 0.5 mph after the installation of DSFS; This particular site had the lowest average speed before DSFS implementation, indicating that DSFS appears to be more effective at locations with more pronounced speed-related issues
City of Bellevue Transportation Department (2009); Real road; Residential neighbourhoods	a) The 85th percentile speed	a) "YOUR SPEED XX"	a) 85th percentile speeds decreased between 0.3 and 6.8 mph over several years
Gehlert et al. (2012); Real road; Before-after study; Residential neighbourhoods	a) Mean speed b) The 85th percentile speed c) The percentage of vehicles exceeding the speed limit	a) A standard DSDS with numeric values corresponding to the driver's actual speed and the words "YOUR SPEED" b) A standard DSDS corresponding to the first sign; In addition, numeric values were highlighted in red or green depending on whether the car driver complied with or exceeded the local speed limit c) The "verbal coloured", where the word "THANK YOU" appeared in green letters when the car driver kept the speed limit and the word "SLOW" in red letters when the driver exceeded the speed limit	a) Each of the DSFS reduces the rider's speed between 0.7–3 km/h b) The verbal-coloured DSFS reduces speed the most, followed by the numeric coloured DSFS and the simple numeric DSFS c) In the long term, the verbal-coloured DSFS also proved to be the most effective
Churchill & Mishra (2016); Real road; Before-after study; Residential neighbourhoods	a) Mean speed b) The 85th percentile speed c) The percentage of vehiclesexceeding the speed limit d) Standard deviation of driving speed	a) "YOUR SPEED" ("SLOW" sign) b) Speed limit with "SLOW DOWN" message ("iSLOW sign")	a) The "SLOW" sign led to an average speed reduction ranging from 1.59 km/h to 5.64 km/h (depending on the specific location) b) The "iSLOW" sign effectively reduced speeding when the trigger speed was reduced from 35 km/h to 30 km/h; However, this beneficial impact was short-term, as speed levels reverted to their pre-installation levels after four weeks
Jue & Jarzab (2020); Real road; Before-after study; Residential neighbourhoods	a) Mean speed	a) Driver's actual speed	a) The average speed reduction was as follows: 0.5 mph after three months, 0.4 mph after six months, 0.8 mph after one year, 0.5 mph after three years and 0.2 mph after five years

the perception of DSFS was positive, with 82.0% of respondents indicating that DSFS contribute to safety enhancement, traffic flow improvement or both.

3.4 Position of DSFS installation, message type and triggering

As mentioned in the previous sections, the efficacy of DSFS is contingent on their placement, the content of their message and the conditions that trigger them. In general, the positioning of warning signs is highly important and serves a dual purpose: to provide drivers with advanced/timely warnings and to address the tendency of drivers to accelerate shortly after passing the sign. Although several studies have evaluated the effectiveness of DSFS, few of them examined the effects of positioning. Of course, positioning depends on the type of road where the DSFS is placed, the speed limit, the setting etc. For example, on straight road sections, the greatest speed reduction was observed 1200 to 1400 feet upstream of the sign [27,40], and speeds began to increase again 300 to 500 feet downstream of the sign [40]. This suggests that the effectiveness of the sign diminishes to some degree once drivers have passed the DSFS, and therefore most researchers recommend installing DSFS at locations where safety is of the utmost importance. For horizontal curves, the optimal location of standard static warning signs is generally about 330 to 650 feet ahead of the curve [41]. Conversely, research focusing on the impact of DSFS on curved road sections revealed that there is not a substantial effect when these signs are positioned 350 ft ahead of the curve, with the optimal DSFS location identified as being 255 ft upstream of the curve [26,42]. However, it should be noted that the optimal location was combined with different messages in the aforementioned studies.

As for the messages, the basic DSFS indicate the driving speed of the approaching vehicle. However, a variety of messages have been used and are listed in *Table 7*.

Table 7 – DSFS messages used in different studies

Message	Study
"YOU ARE SPEEDING SLOW DOWN", "HIGH SPEED SLOW DOWN", "REDUCE SPEED IN WORK ZONE", "EXCESSIVE SPEED SLOW DOWN"	Garber & Patel (1994)
"YOU ARE SPEEDING!!!" alternated with "SPEED LIMIT 45 MPH"	Thompson (2002)
"YOU ARE SPEEDING, SLOW DOWN NOW" for vehicles travelling 5 mph over the posted work zone speed limit of 45 mph and displayed "ACTIVE WORK ZONE, REDUCE SPEED"	Wang et al. (2003);
"YOU ARE SPEEDING" followed by "SLOW DOWN", "YOUR SPEED IS______" followed by "SLOW DOWN", "YOUR SPEED IS______" followed by "THANKS FOR NOT SPEEDING" or "SLOW DOWN", and "YOU ARE SPEEDING" followed by "MINIMUM FINE $200"	Sorrell et al. (2007)
"YOUR SPEED XX MPH" with alternating "POSSIBLE FINE $XXX"	Roberts & Smaglik (2012)
"SHARP CURVE AHEAD" for speeds less than 50 mph, "YOUR SPEED XX MPH" for speeds from 50 to 70 mph, and "YOUR SPEED IS OVER 70 MPH" for speeds above 70 mph	Monsere et al. (2005)
"YOUR SPEED" with a "SLOW DOWN" message	Gates et al. (2020), Mahmud et al. (2021)

Overall, full-matrix displays that can switch between showing the current driving speed and providing supplementary warnings like "SLOW DOWN" when the driver surpasses the speed threshold have been observed to be more effective than signs that solely display the driver's speed [17, 18, 19, 34]. Finally, triggering has also been mentioned as a possible factor, although more solid evidence is lacking. In most studies, triggering speed was set relative to the speed limit. As described in the previous paragraph, some studies have displayed different messages depending on speed [10, 18] however, some researchers have also suggested that uniform triggering may not be appropriate for the dynamic nature of traffic as well as for warning different types of vehicles. Jomaa et al. investigated the effects of triggering speed on driving speed and its standard deviation [43]. The primary goal was to investigate the influence of the trigger speed on both the average speed and the standard deviation. Additionally, the study aimed to identify the trigger speed that strikes the most suitable balance between lowering the crash rate and mitigating the severity of crashes. The findings suggest that the standard deviation was high when the trigger speed was around the speed limit. However, a significant reduction in the standard deviation was observed when the threshold was established at the 85th percentile. In the follow-up study, the authors attempted to model and predict the most suitable trigger speed, considering variables such as vehicle types and road conditions [44]. Adaptive neuro-fuzzy inference systems and random forest was used to predict the speed based on the average speed, traffic flow and the standard deviation of vehicle speeds. Notably, findings indicated that random forest can effectively assist in determining appropriate trigger speeds.

3.5 Temporal effect of the DSFS

As with any other speed reduction measure, the effectiveness of DSFS over time is an important factor in deciding whether to implement it. The temporal effect, of course, depends on the setting, the location of the DSFS and the message type. This section focuses only on the effects of setting due to the lack of studies that address the effects of DSFS position and message type on temporal effect.

In the work zone, speed reduction was maintained for three, five or at least up to seven weeks [4, 6, 9] suggesting long-term effects.

Ullman and Rose's study revealed that the average speed of passenger vehicles decreased by 2.1 to 3.5 mph in the short term, alongside a significant reduction in the percentage of vehicles exceeding the speed limit which was recorded in both short and long term [17]. Hallmark et al. reported a decline in average speeds of 1.82 mph, 2.57 mph and 1.97 mph at one month, 12 months and 24 months following installation, respectively. Additionally, their findings indicated a significant reduction in the percentage of vehicles travelling 5 mph above the advisory speed or the posted speed limit, with reductions of 11.8 percent, 18.6 percent and 19.8 percent after one month, 12 months and 24 months post-installation, respectively [19].

In transition zones, Ullman and Rose recorded a decrease of 3.4 mph and 2.6 mph in the average speed short-term after DSFS installation, while this effect was reduced in the long term (1.4 mph) [17]. Hallmark et al. pointed out that after one month of installation, the average driving speed dropped by 8 mph and speeding by 45 percent [19].

Ullman and Rose reported a short-term average speed reduction of 9.2 mph and a long-term reduction of 8.8 mph following the installation of DSFS on arterial roads [17]. In contrast, within the same context, Ardeshiri and Jeihani discovered that the effectiveness of DSFS was significantly reduced in the long term [45].

In school zones, studies suggest that DSFS have a long-term effect: O'Brien and Simpson highlighted 3 to 4.5 mph reduction over one year after the installation [30]; Williamson et al. recorded that 80% of drivers reduced their speed one year after the DSFS installation [31]; Jue and Jarzab found that speed reduction was 0.5 mph after three months, 0.4 mph after six months, 0.8 mph after one year, 0.5 mph after three years and 0.2 mph after five years [46].

3.6 Effect of the vehicle type

Researchers also evaluated the effects of DSFS on drivers of different vehicles, primarily cars and trucks. Several studies found no significant differences in speed reduction between cars and trucks [4, 11, 18]. Some studies found that the effect of speed reduction was greater for passenger cars than for other vehicles (heavy vehicles) [1, 6, 9], while several recent studies found that DSFS had greater effects on drivers of heavy vehicles [7, 26, 42].

4. DISCUSSION AND CONCLUSIONS

Excess speed is one of the main causes of fatalities worldwide, and lowering excess speeds can significantly reduce, most importantly human losses, but also social and economic losses. One speed reduction measure is dynamic speed feedback signs whose main purpose is to alert drivers about their excessive speed and thus influence their behaviour in a way that they reduce their driving speed.

Although there are a limited number of studies that have examined the safety effects of DSFS, all have demonstrated its beneficial effects. However, the range of crash reductions is quite large, ranging from 5 to 45 percent. Further research on the safety effects of DSFS is needed for different settings and vehicle types to develop more specific implementation strategies and recommendations.

Furthermore, the effectiveness of DSFS is influenced by their positioning and messaging strategy. Unfortunately, we were unable to gain more precise insights into the positioning of DSFS due to differences in settings, speed limits and other specific characteristics of the studied locations. Nevertheless, when deciding where to install the DSFS, one should consider the speed limit, general effectiveness of the DSFS and 85th percentile speed of the traffic flow to determine which positioning is most appropriate to achieve the greatest positive effect. In terms of the messages, a variety of strategies have been employed – from displaying only driving speed to a variety of other messages such as “SLOW DOWN”, “YOU ARE SPEEDING SLOW DOWN”, YOUR SPEED XX MPH”, etc. In general, messages should not be too long and should not require drivers to pay too much attention while reading to avoid distraction. Moreover, certain studies propose that the most significant improvement in driver behaviour may be attained when the feedback message alternates between displaying the current speed and a "SLOW DOWN" message [26, 42]. However, such a messaging strategy may not be equally effective in all settings and situations. Overall, for maximum impact, the messaging strategy should be based on the components of protection motivation theory (perceived severity, counter-rewards, vulnerability) [47].

In addition, triggering has also been mentioned as a potential factor that may affect the efficacy of DSFS. Usually, triggering is based on a specific speed threshold. However, some researchers point out that such a uniform triggering may not be appropriate for the dynamic nature of traffic as well as for warning different types of vehicles [43, 44]. Nevertheless, we lack more solid evidence and further research is needed to develop more specific recommendations.

When considering the operational benefits of DSFS, it is important to consider traffic flow, i.e. what type of vehicles mainly pass through the given road section. Analysed studies suggest that the impact of DSFS on drivers of different vehicles varies. Because all studies used different methodologies, settings, DSFS locations and message types, and data samples, it is difficult to draw more concrete conclusions. However, Flynn et al. suggested in their meta-analysis that there may be no difference in the effect of DSFS on different vehicles because heavier vehicles travel more slowly than passenger cars and therefore may reduce their speed less [1]. More research is needed to further substantiate this.

Finally, most studies examined the short-term effects of DSFS, and as with other traffic control measures, their long-term effectiveness may be questionable. Overall, DSFS showed positive effects in the short term in all studies, but these effects diminished to some extent over time. However, most studies suggest that speed reduction can be successfully achieved over a longer period of time. Nevertheless, further research is needed on this topic to determine how long the effects of DSFS last and what strategies can be used to prolong their effectiveness.

Overall, it can be concluded from this literature review that several factors, ranging from the configuration of the environment, the location of the DSFS, the type of message and strategy and the configuration of the traffic flow, should be taken into account in order for DSFS to be effective and provide the desired operational and safety benefits.

Nevertheless, we have identified general guidelines that should be followed:

1) DSFS should be installed at critical roadway locations where safety is of paramount importance;
2) The placement of DSFS should take into account the specific characteristics of the setting/location and the signs should be placed so that they are clearly visible to drivers under all conditions;
3) The sign feedback mechanism should be carefully designed to provide clear and accurate feedback to drivers;
4) The messaging strategy should be based on the protection motivation theory components (perceived se-

verity, counter-rewards, vulnerability) and tailored to the specific location and situation; messages should be simple, short and easy for drivers to understand (displaying the speed number alternating with the message “SLOW DOWN” might provide the most benefit);

5) Factors such as road geometry, average speed, traffic flow and its characteristics, presence of pedestrians or cyclists and standard deviation of vehicle speed should be considered when determining the appropriate trigger speed; if a uniform trigger speed is used, the aforementioned threshold should be set at the 85th percentile speed;
6) DSFS must be properly maintained and function properly to achieve the desired effect.

4.1 Recommendations for research related to DSFS

As outlined in this review, several studies have looked at the effect of DSFS in various settings, with inconsistent or unclear results in some areas. Although studies have demonstrated that the presence of DSFS reduces driving speed, there are a limited number of studies that have evaluated the safety benefits of the aforementioned speed reduction. Moreover, crash reduction varied significantly in the studies that addressed this issue. Therefore, future research should focus on investigating the safety effects of DSFS to determine the cost-benefit ratio of such a measure in different settings. In addition, future research should focus on investigating the optimal position and messaging strategy for different settings.

As with many other road safety measures that focus on influencing drivers’ behaviour, the temporal impact of DSFS is questionable, and due to the different settings, positioning and messaging strategies, the results of studies that have addressed this issue are mixed and may not be fully comparable. Future studies should focus on this issue and examine how different settings and messaging strategies affect the temporal impact of DSFS.

Moreover, we recommend that DSFS are tested as a part of the Road and Weather Information System (RWIS) to warn motorists of adverse weather conditions (for example for Bridge Deck Warning Systems), as well as in new settings such as tunnel entrances, intersections of high-speed roads or for “black spots”, i.e. road segments with high crash rates.

4.2 Limitations of the study

Although this study provides a comprehensive overview of the use and benefits of DSFS, there are two main limitations that should be considered. First, only studies published in an English-language peer-reviewed journal, conference proceedings or as a technical report were included. Due to the language barrier, we did not include studies in other languages, although they could provide valuable results and insights. Second, scientific publications were searched only in the Web of Science (WoS) database. Although the aforementioned database contains several of the major scientific databases, some of the studies containing important findings may have been overlooked.

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Pregled literature vezano uz utjecaj dinamičkih znakova s povratnom informacijom o brzini na smanjenje brzine vožnje na različitim kritičnim lokacijama

Sažetak

Prekomjerna brzina jedan je od glavnih uzroka prometnih nesreća sa smrtnim ishodima diljem svijeta. Jedna od mjera smanjenja brzine su preventivni radarski mjerači s pokazivačem brzine kretanja vozila (DSFS), čija je glavna svrha upozoriti vozače na njihovu prekomjernu brzinu i tako utjecati na njihovo ponašanje i smanjenje brzine vožnje. Cilj ovog preglednog rada je raspraviti prednosti implementacije DSFS-a u različitim okruženjima, identificirati najučinkovitije strategije postavljanja i poruka, analizirati javno mišljenje i temporalni učinak DSFS-a te identificirati potencijalna mjesta gdje se navedena mjera može implementirati. Istraživanje uključuje 44 rada, od kojih je 35 članaka u znanstvenim časopisima, tri su radovi s konferencije, a šest su tehnički izvještaji. Identificirana istraživanja podijeljena su u šest kategorija prema njihovoj temi: 1) Operativne prednosti DSFS-a; 2) Sigurnosne prednosti DSFS-a; 3) Javno mišljenje o DSFS-u; 4) Položaj instalacije DSFS-a, vrsta poruke i okidač; 5) Temporalni učinak DSFS-a; i 6) Učinak vrste vozila. Rezultati ove studije pružaju informacije o upotrebi DSFS-a i kao takvi su vrijedni za cestovne vlasti i istraživače.

Ključne riječi

dinamički znakovi s povratnom informacijom o brzini; brzina vožnje; ponašanje vozača; sigurnost cestovnog prometa; pregled literature.

APPENDIX

Summary of the methodological approaches and main findings of analysed studies

Authors and year	Type of study/Setting	Variables/Message type	Main results
Garber & Patel (1994)	Real road; Before-after study Work zone	Main variables: a) Mean speed b) 85th-percentile speed Message type: a) "YOU ARE SPEEDING SLOW DOWN" b) "HIGH SPEED SLOW DOWN" c) "REDUCE SPEED IN WORK ZONE" d) "EXCESSIVE SPEED SLOW DOWN"	a) Significant reduction in the average speed of vehicles travelling≥ 59 mph b) Speed reduction of 8 to 10 mph after DSFS installation
Garber & Srinivasan (1998)	Real road; Before-after study	Main variables: a) Mean speed b) 85th-percentile speed c) Speed variances d) Percentages of vehicles speeding Message type: a) "YOU ARE SPEEDING SLOW DOWN"	a) Speeds were reduced by 8-10 mph in the middle of the work zone for both cars and trucks b) In long work zones, vehicles tend to increase speed towards the end of the work zone
McCoy et al., (1995)	Real road; Before-after study	Main variables: a) Mean speeds b) Percentages of vehicles exceeding the advisory speed limit Message type: a) "YOUR SPEED"	a) Average speed of 4 mph for vehicles with two axles and 5 mph for vehicles with more than two axles b) 20 to 40 percent decrease in the number of vehicles exceeding the speed limit by 10 mph
Pesti & McCoy (2001)	Real road; Before-after study Work zone	Main variables: a) Mean speed b) Standard deviation c) 85th-percentile speed d) Percentage complying with the speed limit e) Percentage complying with the speed limit plus 8 km/ h f) Percentage complying with the speed limit plus 16 km/h Message type: a) Driver's actual speed with sign "SPEED LIMIT 55"	a) Reduction of average speed by 3 to 4 mph b) Reduction of 85th-percentile speed by 2 to 7 mph c) 20 to 40 percent increase in vehicles obeying speed limits and speed threshold
Fontaine & Carlson (2001)	Real road; Before-after study Work zone	Main variables: a) Mean speed b) Percentage complying with the speed limit Message type: a) Driver's actual speed	a) Speed reduction between 3.2 and 14.5 km/h (2 to 9 mph) for passenger cars and between 11.3 and 16.1 km/h (7 to 10 mph) for heavy vehicles b) Decrease in the number of vehicles exceeding the speed limit by 15 to 20 percent
Thompson (2002)	Real road; Before-after study Work zone	Main variables: a) Mean speed b) Percentage complying with the speed limit Message type: a) "YOU ARE SPEEDING!!!" and "SPEED LIMIT 45 MPH"	a) Reduction of the average speed by 7 mph b) Reduction of the number of vehicles exceeding the speed limit by 11 percent
Wang et al. (2003)	Real road; Before-after study Work zone	Main variables: a) Mean speed b) Speed variance Message type: a) "YOU ARE SPEEDING, SLOW DOWN NOW" for vehicles travelling 5 mph above the 45 mph speed limit b) "ACTIVE WORK ZONE, REDUCE SPEED" for vehicles travelling less than 50 mph	a) The average operating speed decreased by 7 to 8 mph, in addition to the reduction in speed deviation b) DSFS effects remained similar during the three-week implementation period
Sorrell et al. (2007)	Real road; Before-after study Work zone	Main variables: a) 85th percentile speed b) Mean speed c) Frequency of speeds d) Number of observed vehicles speeding Message type: a) "YOU ARE SPEEDING" followed by "SLOW DOWN" b) "YOUR SPEED IS _" followed by "SLOW DOWN" c) "YOUR SPEED IS _" followed by "THANKS FOR NOT SPEEDING" or "SLOW DOWN" d) "YOU ARE SPEEDING" followed by "MINIMUM FINE $200"	a) The average speed decreased from 6 mph (9.7 km/h) above the speed limit to speeds generally within 2 mph (3.2 km/h) above the speed limit b) The 85th percentile speed decreased to approximately 5 mph (8.0 km/h) over the speed limit c) Compliance with the posted speed limit improved significantly (up to 61%)

Summary of the methodological approaches and main findings of analysed studies

Authors and year	Type of study/Setting	Variables/Message type	Main results
Roberts & Smaglik (2012)	Real road; Before-after study Work zone	Main variables: a) Mean speed b) Speed medians c) The 85th percentile speed d) Percentage of vehicles that exceeded the speed limit Message type: a) “YOUR SPEED XX MPH,” alternating with “POSSIBLE FINE $XXX”	a) A small reduction in average speeds was observed, but a significant reduction in the number of high-speed vehicles was observed, from 25% for speed feedback messages to 50% for speed feedback and fines b) Speed-only feedback reduced 85-percentile speed by 2 mph, while 85-percentile speed was reduced by 3 mph when speed feedback alternated with fine feedback c) Significant reductions in the percentages of speeders
Zhang & Gambatese (2017)	Real road; Work zone	Main variables: a) Mean speed b) Difference in mean speed Message type: a) “SLOW FOR WORKERS” b) “WORKERS ON ROAD”	a) Combination The combination of portable changeable message signs on trailers and radar speed displays is most effective in reducing vehicle speeds immediately at the end of the taper, although the effect may not be the same over longer distances in a work zone
Banerjee et al. (2019)	Driving simulator Work zone	Main variables: a) Mean speed Message type: a) “YOUR SPEED IS _”	a) The overall reduction in speed was approximately 8 mph for DSFS
Anderson et al. (2021)	Real road; Before-after study Work zone	Main variables: a) Mean speed b) Speed compliance Message type: a) Driver’s actual speed	a) Speed reduction by 2 mph b) Passenger cars and semi-trucks most often exceed the speed limit
Tribbett et al. (2000)	Real road; Before-after study Horizontal curves	Main variables: a) Mean speed b) Changes in speed c) Lane line encroachments d) Brake light actuation e) Crash rate f) Public perception Message type: a) “50 MPH CURVE AHEAD” b) “50 MPH CURVES” c) “YOUR SPEED AHEAD 70 MPH”	a) The results varied by site - at some sites the average speed decreased, while at others it remained unchanged or increased b) Results were also inconsistent for different types of vehicles c) The study reported a decrease in lorry-related crashes overall and mixed results for passenger vehicle crash-es; however, the study was unable to conclude due to limited data on crashes during the follow-up period d) On average, 80.0 percent of drivers found the information provided by DSFS useful
Ullman & Rose (2005)	Real road; Before-after study Horizontal curves Speed transition zones Arterials School zones	Main variables: a) Mean speed b) The 85th percentile speed c) Percentage of vehicles that exceeded the speed limit Message type: a) “YOUR SPEED IS _”	Horizontal curves: a) The average speed of passenger cars decreased by 2.1 to 3.5 mph in the short term, while the effect on the speed of trucks was not comparable b) The percentage of vehicles exceeding the posted speed limits decreased significantly in both the short and long term Transition zones: a) Average speed decreased by 3.4 mph and 2.6 mph in the short term and by 1.4 mph in the long term b) Drivers who exceeded the posted speed limit decreased their speed significantly compared with drivers who obeyed the speed limits Arterials: a) In the short term, average speed decreased by 3.4 to 3.6 mph b) In the long term, the effects of speed reduction were inconsistent - at one site, average speed returned to previous conditions; at another, average speed was 4.0 mph below previous conditions School zones: a) Average speed was reduced by 9.2 mph in the short term and 8.8 mph in the long term b) The number of drivers who exceeded the speed limit dropped from 95 percent to 34 percent in the short term and 44 percent in the long term c) A small but significant decrease in speeds was also recorded at times when the school zone (and DSFS) was not active

Summary of the methodological approaches and main findings of analysed studies

Authors and year	Type of study/Setting	Variables/Message type	Main results
Monsere et al. (2005)	Real road; Before-after study Horizontal curves	Main variables: a) Mean speed b) Changes in speed distribution Message type: a) "SHARP CURVE AHEAD" if the speed was below 50 mph b) "YOUR SPEED XX MPH" if the detected speed was between 50 and 70 mph c) "YOUR SPEED IS OVER 70 MPH" if the detected speed was above 70 mph	a) The average speed was reduced by 3 mph in one direction and 2 mph in the other direction b) The speed distributions of cars and trucks were statistically different c) A small percentage of vehicles were found to be travelling over 70 mph when the DSFS was active
Hallmark et al. (2015)	Real road; Before-after study Horizontal curves	Main variables: a) Mean speed b) Speed compliance c) Crash data Message type: a) "YOUR SPEED XX" for drivers travelling over the 50th percentile speed up to 20 mph over the posted speed limit b) "SPEED LIMIT XX" for drivers travelling 20 or more mph over the speed limit c) Curve warning sign showing a curve sign and an alternating slowdown message to the vehicles exceeding 50th percentile speed	a) Significant reduction in average speed of 1.82 mph, 2.57 mph and 1.97 mph at 1 month, 12 months and 24 months after installation, respectively b) Significant reduction in the percentage of vehicles exceeding the advisory speed or posted speed limit by 5 mph by 11.8 percent, 18.6 percent and 19.8 percent after 1 month, 12 months and 24 months, respectively c) The percentage of vehicles exceeding the advisory or posted speed limit by 10 mph, 15 mph, or 20 mph decreased by even greater amounts d) Overall, 5 to 7 percent fewer crashes in the first three years after DSFS installation
Montella et al. (2015)	Driving simulator Horizontal curves	Main variables: a) Mean speed b) Deceleration rate Message type: a) "YOUR SPEED XX"	a) DSFS reduced the driving speed at the beginning of the curve from 55 mph to 51 mph
Mahmud et al. (2022)	Real road; Before-after study Horizontal curves Speed transition zones	Main variables: a) Mean speed b) The percent change between the fraction of vehicles exceeding the posted or advisory speed Message type: a) "YOUR SPEED XX" b) "YOUR SPEED XX" with alternating "SLOW DOWN" message	Horizontal curves: a) DSFS provided a significant reduction in the percentage of vehicles entering the curve at speeds 5 or 10 mph above the curve advisory speeds b) Speed at the curve entry reduced by 0.1 to 2.8 mph when the DSFS was installed at the point of curvature and by 0.7 to 3.5 mph when it was installed at the curve advisory speed sign c) The number of vehicles travelling 10 mph above the curve advisory speed was reduced by 25 to 40 percent Speed transition zones: a) The greatest speed reduction occurred at the DSFS site - speeds were 3.2 to 7.8 mph lower when the sign was in operation b) At the reduced speed limit sign, the speed reduction is between 3.6 and 6.2 mph c) It has been determined that speeding is 78.8 to 92.4 percent less likely to occur in the presence of the DSFS
Sandburg et al. (2009)	Real road; Before-after study Speed transition zones	Main variables: a) Mean speed b) 50th (median), 85th and 95th percentile speeds c) 10-mph Pace Message type: a) "YOUR SPEED XX"	a) Significant decrease in mean and 50-, 85-, and 95-percentile speeds, especially at the sites with higher speed differentiate between the upstream and reduced speed limits b) 85th percentile speeds decreased by 7.0 mph, 7.5 mph, 6.3 mph and 6.8 mph after 1 week, 2 months, 7 months and 12 months of installation, respectively c) The greatest speed reduction was recorded at higher speeds - 95th percentile - up to 9 mph d) Speed decreased by 10 mph from an initial 41-50 mph to 31-40 mph within the first week and to 31-40 mph at one year with essentially the same percentage of vehicles
Cruzado & Donnell, 2009	Real road; Before-after study Speed transition zones	Main variables: a) Mean speed Message type: a) Driver's actual speed	a) The average speed reduction for free-flowing passenger cars was approximately 6.3 mph (10.1 km/h), ranging from 0.8 to11.9 mph (1.3 to 19.2 km/h) b) The effectiveness of the DSFS persisted during the time the DSFS was activated but diminished once it was removed
Hallmark et al. (2015)	Real road; Before-after study Speed transition zones	Main variables: a) Speeds while traversing through the transition zone b) Probability of a vehicle exceeding the posted speed limit at the start of the reduced speed limit zone Message type: a) Driver's actual speed	a) Simple speed feedback sign - Average speeds decreased by 5 to 8 mph and 85th percentile speeds decreased by 3 to 9 mph - The percentage of vehicles exceeding the speed limit by 5 mph or more decreased from 12 to 62%, by 10 mph or more from 25 to 73%, and by 15 mph or more from 38 to 79% b) A single sign with alphanumeric capabilities - The average speed decreased by 5 mph and the 85th percentile speed decreased by 7 mph - The percentage of vehicles exceeding the posted speed limit by 5, 10, and 15 mph or more mph decreased by 76, 91 and 92 percent, respectively c) Standard speed limit sign with LED lights activated when a driver is going 5 mph or more mph over the posted speed limit - Inconsistent results - Average speed dropped between 0.5 and 5 mph and 85 percentile speed dropped between 1 and 6 mph - The percentage of vehicles exceeding the posted speed limit by 5, 10, or 15 mph or more decreased between 10 and 25 percent, 11 and 40 percent and 50 percent, respectively

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Gates et al. (2020)	Real road; Before-after study Freeway exit ramp	Main variables: a) Speed at the point of curvature (curve entry) b) Probability of initial brake response occurring between 200 and 600 ft upstream of the PC c) Probability of a vehicle entering the curve below 45 mph Message type: a) “YOUR SPEED XX” b) “YOUR SPEED XX” alternated with the “SLOW DOWN” message when >40 mph and the advisory speed panel	a) Curve entry speeds were generally lower for all DSFS test conditions and vehicle types b) Vehicle speed measured 1,000 ft before the curve correlated strongly with speed at the point of curvature for all speed models c) When DSFS was installed 255 ft upstream of the curve, speeds at the curve entry were reduced by 0.54 to 1.47 mph d) When DSFS was installed directly at the point of curvature, speeds at the curve entry speeds reduced by 0.68 to 1.08 mph e) The DSFS had no significant effect on curve entry speeds when installed at the location farthest upstream of the curve (450 ft) f) The DSFS had the greatest effect on the curve entry speeds when displaying the speed number combined with an alternating “SLOW DOWN” message for vehicles 10 mph above the advisory speed g) Removal of the “SLOW DOWN” message in such a way that only the speed digits were displayed as feed-back resulted in a significant degradation of speed reduction h) Speed reductions for passenger cars at the curve entry generally ranged from 0.5 to 1.5 mph; for trucks and buses, curve entry speeds were, on average, 1.54 mph lower, while the speeds cited for tractor-trailers were 5.07 mph lower when the DSFS was in operation at the location
Mahmud et al. (2021)	Real road; Before-after study Freeway exit ramp	Main variables: a) Mean speed b) Probability of initial brake response occurring between 200 and 600 ft upstream of the point of curvature c) Probability of a vehicle entering the curve within 15 mph of the advisory speed Message type: a) “YOUR SPEED XX” b) “YOUR SPEED XX” alternated with the “SLOW DOWN” message when >40 mph and the advisory speed panel	a) Curve entry speeds were approximately 2.0 to 2.3 mph lower with the DSFS when the sign was placed directly at the point of curvature b) The DSFS installed at the point of curvature also reduced the occurrence of excessive curve entry speeds - drivers were 1.7 to 2.5 times more likely to enter the curve at less than 15 mph the curve advisory speed c) The DSFS improved braking performance when placed at the point of curvature - drivers were 1.4 to 1.8 times more likely to initiate braking between 200 and 600 ft upstream of the curve d) The DSFS had the greatest effect on reducing speed at the entrance to the curve during off-peak hours of the day. The magnitude of this speed reduction due to the DSFS (0.9 mph) is nearly twice that during the peak hours (0.5 mph) and three times that during the night-time hours (0.3 mph) e) The DSFS had a similar effect on driver response in all vehicle categories
City of Bellevue Transportation Department (2009)	Real road; Arterials Residential neighbourhoods	Main variables: a) The 85th percentile speed Message type: a) “YOUR SPEED XX”	Arterials: a) The reduction in 85th percentile speed ranged from 2.0 to 6.3 mph b) Significant speed reduction was observed over multiple years of observation Residential neighbourhoods: a) 85th percentile speeds decreased between 0.3 and 6.8 mph over several years
Ardeshiri & Jeihani (2014)	Real road; Before-after study Arterials	Main variables: a) Mean speed b) Compliance with the speed limit Message type: a) Driver’s actual speed	a) The mean speeds before- and- after indicated that the DSDS is an effective short-term tool for short-distances b) Changes in speed limit compliance due to DSDS, upstream speed limit compliance, time of day and day of week
Karimpour, Kluger, & Wu (2021)	Real road; Before-after study Arterials	Main variables: a) Number of vehicles arriving at an intersection, aggregated every 15-min by each approach b) The percentage of vehicles that arrived at the intersection when the signal was red c) Total amount of time that all vehicles spend in the intersection queue while waiting to pass the intersection d) The occurrence of left-over demand for a specific approach at an intersection e) The average vehicle operating speed on each roadway links Message type: a) “YOUR SPEED XX” alternated with the “SLOW DOWN” message when driving speed is above 10 mph of the posted limit	a) A significant effect of DSFS on measures of signal performance measures and consequently on arterial mo-bility at the intersection level was not recorded b) Link speed before and after DSFS deactivation had a similar peak value; however, average speeds were higher before DSFS than after DSFS c) The effect of DSFS on drivers’ behaviour depends on their approach speed - drivers within certain speed bins behave differently after being informed of their speed by DSFS d) The dollar-per-year benefits associated with a reduction in serious crashes on the studied arterials with active DSFS showed promising safety improvements
Karimpour et al. (2021)	Real road; Before-after study Arterials	Main variables: a) Mean speed b) Probability of not obeying the speed limit c) Probability of going 5 mph over speed limit Message type: a) “YOUR SPEED XX”	a) DSFS alone decreased average speeds by 0.8 mph to 5.8 mph; at a site with a higher speed limit (50 mph), average speeds increased at the location with DSFS b) When DSFS was supported with periodic law enforcement operations, travel speeds at DSFS sites decreased by 0.3 to 2.5 mph c) An additional drop of 2.5 mph to 3.5 mph beyond the point of DSFS was observed with the presence of enforcement
O’Brien & Simpson (2012)	Real road; Before-after study School zones	Main variables: a) Mean speed b) The 85th percentile speed c) The percentage of vehicles exceeding the speed limit d) Standard deviation and pace speed Message type: a) “YOUR SPEED XX”	a) The average speed was 3.8 mph lower 12 months after the installation of the signs b) No equivalent, consistent, and sustained reduction in vehicle speeds was observed outside of school hours, when the sign was deactivated, as during school hours c) Different vehicle speeds depending on the direction of travel outside school hours d) If the direction of travel is not considered, the average speed outside of school hours increased slightly (0.45 mph) 12 months after the signs were installed

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Williamson et al. (2016)	Real road; Before-after study School zones	Main variables: a) The 85th percentile and mean speeds exceeding the posted speed limit by 5 mph b) The 85th percentile and mean speeds exceeding the posted speed limit by 3 mph Message type: a) “YOUR SPEED XX”	a) 85.6% of drivers who exceeded the speed limit reduced their speed after DSFS installation b) One year later, after the installation of DSFS, 80.0% of drivers who exceeded the speed limit reduced their speed c) The reduction in vehicle speed ranged from 0 to 13 mph (depending on the study group)
Bloch (1998)	Real road; Before-after study Residential neighbourhoods	Main variables: a) Mean speed b) Percentage of vehicles travelling≥ 16 km/h over the speed limit Message type: a) “YOUR SPEED XX”	a) Speed reduced at the trailer location by an average of 6.1 mph; speed reductions downstream of the trailer were 2.9 mph without enforcement and 5.9 mph with enforcement b) One week after speed trailer removal, speed reductions of 0.6 mph (at the former trailer location) and 1.7 mph (downstream) were observed for operations that did not coincide with enforcement; when enforcement occurred in conjunction with the speed trailer, speed reductions of 0.6 mph occurred one week after sign removal at both the trailer location and downstream of the trailer
Chang et al. (2005)	Real road Residential neighbourhoods	Main variables: a) Mean speed b) The 85th percentile speed Message type: a) “YOUR SPEED XX”	a) Speed decreased significantly at three of the four sites (between 1.2 and 2.2 mph); at one site, speed increased by 0.5 mph after DSFS installation, but this site previously had the lowest average speed, suggesting that DSFS implementation is more effective at sites with greater speed-related problems
Gehlert et al. (2012)	Real road; Before-after study Residential neighbourhoods	Main variables: a) Mean speed b) The 85th percentile speed c) The percentage of vehicles exceeding the speed limit Message type: a) A standard DSDS with numeric values corresponding to the driver’s actual speed and the words “YOUR SPEED” b) A standard DSDS corresponding to the first sign; In addition, numeric values were highlighted in red or green depending on whether the car driver complied with or exceeded the local speed limit c) The “verbal coloured”, where the word “THANK YOU” appeared in green letters when the car driver kept the speed limit and the word “SLOW” in red letters when the driver exceeded the speed limit	a) Each of the DSFS reduces the rider’s speed between 0.7–3 km/h b) The verbal-coloured DSFS reduces speed the most, followed by the numeric-coloured DSFS and the simple numeric DSFS c) In the long term, the verbal-coloured DSFS also proved to be the most effective
Churchill & Mishra (2016)	Real road; Before-after study Residential neighbourhoods	Main variables: a) Mean speed b) The 85th percentile speed c) The percentage of vehicles exceeding the speed limit d) Standard deviation of driving speed Message type: a) “YOUR SPEED” (“SLOW” sign) b) Speed limit with “SLOW DOWN” message (“iSLOW sign”)	a) The average speed with the “SLOW” sign has decreased by 1.59 km/h to 5.64 km/h, depending on the location, compared to the period before installation b) the “iSLOW” sign reduced speeding when the trigger speed was lowered from 35 km/h to 30 km/h. However, the positive effect did not last long, as speed levels returned to pre-installation levels after 4 weeks of “iSLOW” installation
Jue & Jarzab (2020)	Real road; Before-after study Residential neighbourhoods	Main variables: a) Mean speed Message type: a) Driver’s actual speed	a) The average reduction in speed was 0.5 mph after three months, 0.4 mph after 6 months, 0.8 mph after one year, 0.5 mph after 3 years and 0.2 mph after 5 years
Wu et al. (2020)	Before-after study	Main variables: a) Crash rate Message type: a) Driver’s actual speed	a) The total number of crashes decreased by 36.1 percent, including 38.0 percent fewer rear-end crashes, 32.5 percent fewer crashes due to improper lane changes, and 38.2 percent fewer speed-related crashes b) The benefit-cost ratio of installing DSFS ranged from 8.16 to 20.19 for the 2-year service life and from 19.84 to 49.06 for the 5-year service life
Wu et al. (2021)	Before-after study	Main variables: a) Crash rate Message type: a) Driver’s actual speed	a) The number of collisions decreased by 31.02 percent on collector segments equipped with DSFS only and by 41.61 percent on segments treated with both DSFS and mobile photo enforcement