METHODS FOR LOWERING SPEEDS AND VULNERABLE ROAD USER INJURIES, WITHOUT PHYSICAL DESIGN TREATMENTS

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ABSTRACT

This review summarizes current literature on the effectiveness of non-infrastructure speed management countermeasures in reducing operating speeds and enhancing the safety of vulnerable road users (VRUs). The paper categorizes these countermeasures into operational, technological, and policy- and education-oriented approaches, and finds that speed cameras provide the most significant benefits in both speed reduction and VRU safety. The summary also highlights that patrol enforcement and signal retiming are among the most effective methods for reducing speeding violations, while operational and technological countermeasures are more extensively documented in relation to VRU safety.

KEYWORDS: Non-infrastructure countermeasures, Operating speed, VRU, Road safety

BACKGROUND

Speeding is a major contributor to traffic crashes, with 12,151 speeding-related fatalities and 300,595 injuries reported in the U.S. in 2022 (NCSA, 2024). The share of speeding-related deaths among all traffic fatalities increased from 27% in 2015 to 29% in 2022, while speeding-related injuries accounted for 13% of all traffic injuries in 2022 (NCSA, 2024). Speeding imposes significant societal costs, including loss of life, vehicle damage, medical expenses, insurance claims, and other economic burdens. According to a report by NHTSA (Blincoe et al., 2022), crashes result in annual economic-only and comprehensive costs of approximately $1,300 and $4,100 per American. Figure 1 shows the percentage of speeding-related traffic fatalities by state in 2022, with Wyoming, New Mexico, and North Carolina reporting the highest shares at 45%, 40%, and 40%, respectively (NCSA, 2024).

Many agencies and researchers have noticed and studied the prevalence of speeding in the U.S (Boyle et al., 1998; Williams et al., 2006; Schroeder et al., 2013; Kim et al., 2022). For instance, the AAA's 2021 Traffic Safety Culture Index Survey (AAA Foundation, 2022) surveyed 2,700 licensed drivers aged 16 and older and found that almost half reported traveling 15 mph over a freeway's posted speed limit (PSL) at least once in the month before their survey response, while 40.2% reported going 10 mph over the speed limit on a residential street (at least once). Beyond survey data, of 12 million vehicles measured at 677 sites across the U.S., more than half of arterial-using vehicles were found to exceed speed limits, with 16-19% exceeding the limit by 10 mph or more on freeways, arterials, and collector roads (De Leonardis et al., 2018). State-level investigations also support these results. For example, Skszek (2004) found that 46% to 69% of vehicles on Arizona highways were exceeding PSLs on highways with PSLs of 55 mph. During Waymo's 10-day study periods in San Francisco and Phoenix urban streets, with over one-million speed observations, almost half the visible/nearby moving vehicles were exceeding the PSL. And 6% of those were driving 10 mph or more above the speed limit on rather low-speed roadways—with PSLs of 40 mph or less (Waymo, 2023). That is an exceedance of 25% or more of the limit, but most police units will not ticket until 5 or 10 mph above the PSL on such roadways and streets (Kockelman and Ma, 2018).

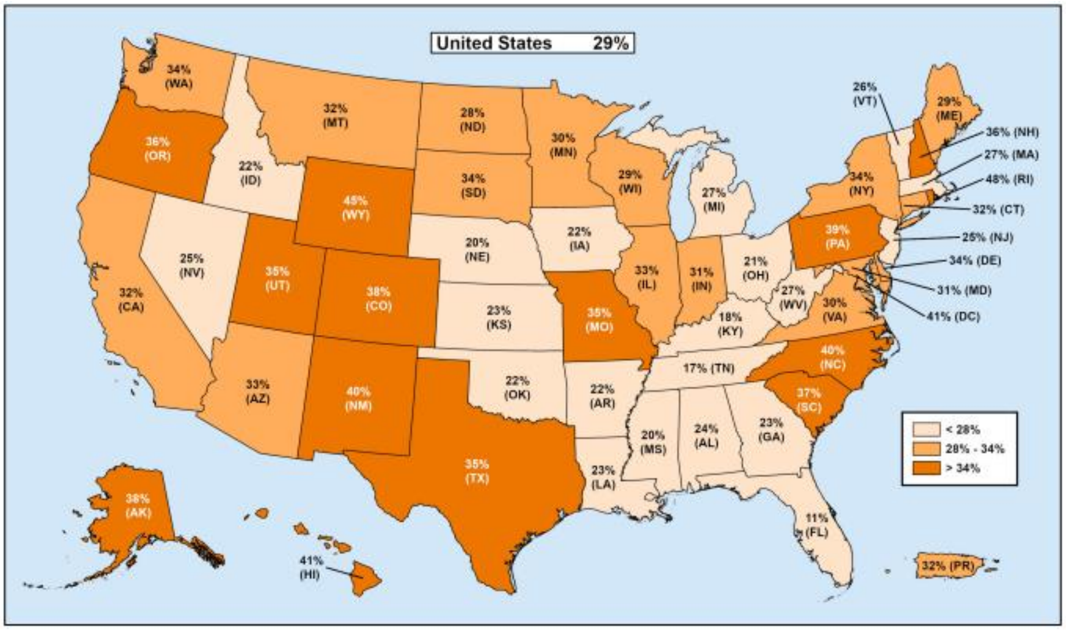

Figure 1: Shares of Speeding-Related Traffic Fatalities by U.S. State in 2022
(Source: NCSA 2024, Fig 8)

Operating speeds are highly related to both the occurrence and severity of crashes. Collisions at higher speeds are more likely to result in severe outcomes (Das et al., 2018). The probability of a car driver being killed in a crash at an impact speed of 50 mph is 15 times higher than the probability of being killed at an impact speed of 25 mph (Joksch, 1993). Specifically, pedestrians, cyclists, and other vulnerable road users (VRUs) are more susceptible to crashes compared to drivers. A European study (Wittink, 2001) reported that crash rates for cyclists were 10 times higher than those for drivers. In addition, the probability of pedestrians being killed by speeding vehicles are extremely high. Rósen et al.'s (2011) review of others' investigations found that only 10% of pedestrians survived 60 mph collision speeds, fewer than 50% survived 50 mph speeds, and nearly all survived 12 mph or lower crash speeds (with roadway vehicles, of various body types). To quantify the relationship between fatality risk and impact speeds, Hussain et al. (2019) did a meta-analysis of 15 studies across China, Germany, Japan, South Korea, the UK and US between 1980 and 2017. Figure 2 illustrates the wide variation in pedestrian risk outcomes, based on data from 36,138 pedestrians struck by the front of motor vehicles. The overall estimate—derived from a meta-regression controlling for pedestrian age, study publication year, country, and data type—is shown in red. A dramatic increase in pedestrian fatality risk was observed as impact speeds rose from 25 mph to 50 mph, following an overall S-shaped pattern.

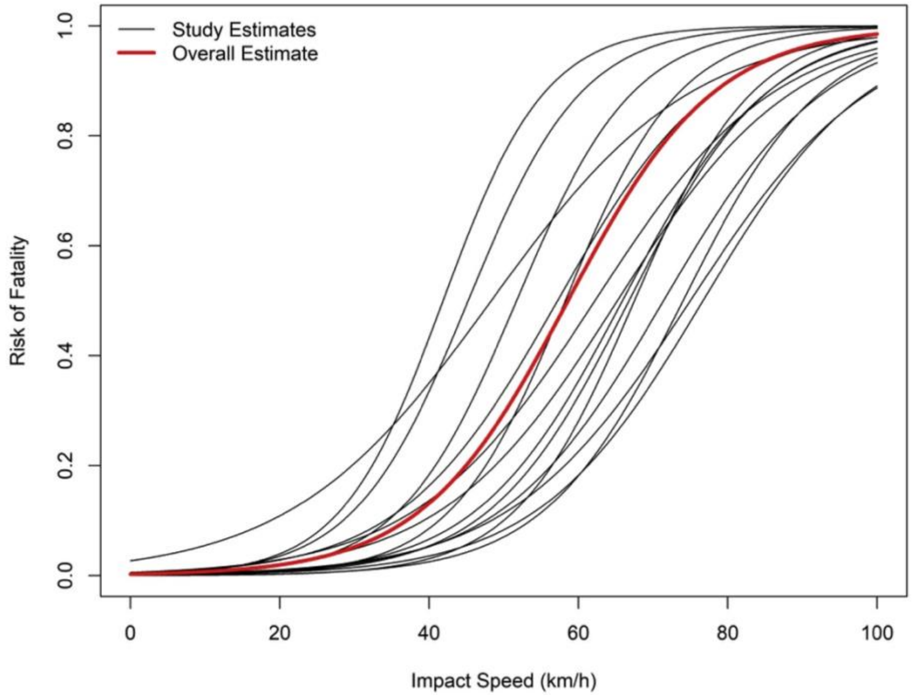

Figure 2: S-shaped Curves for Pedestrian Fatality Risk by Impact Speed
(Source: Hussain et al., 2019, Fig. 5)

To control speeding behaviors and better protect all road users, speed management for safer roadways has always been one of the FHWA's (2024) five focuses when listing 28 suggested countermeasures and strategies. Infrastructure treatments, including speed humps, chicanes, curb extensions, and non-infrastructure strategies, such as variable speed limits and speed enforcement, have been proven to be effective in many research studies and documents (Shin et al., 2009; Fitzpatrick et al., 2014; Tony, 2020; New York City, 2023). In such evaluations, cost-benefit analysis is typically included. For instance, Kockelman et al. (2021) developed a methodology for selecting roadway treatment strategies and estimated crash modification factors (CMFs) to assess their effectiveness. Among all physical treatments, curb ramps, speed trailers, bollards, and raised center medians were found to be the most effective, with CMFs of approximately 0.93. The study also evaluated several non-physical treatments, including PSL adjustments and safety campaign implementations. Results showed that these non-physical treatments can significantly reduce crashes, with CMFs ranging from 0.705 (for a 5% decrease in speed limits) to 0.93 (for the Safe Routes to School program). Additionally, FHWA (2018) provided a toolbox to calculate the overall benefits of countermeasures. Regarding costs, both federal and local governments provide estimates depend on the respective countermeasures. For example, in the case of infrastructure treatments, Kockelman et al. (2021) estimated an average cost of $2,640 for each speed hump, $9,960 for each chicane, and $13,000 for each curb extension, for application by the Texas DOT (TxDOT).

Although non-infrastructure countermeasures remain an essential component of speed management and transportation policy, their impacts on operating speeds and VRU safety have been insufficiently studied compared to physical countermeasures. This study summarizes existing non-infrastructure strategies and their associated safety benefits. These strategies are categorized into three groups—operational, technological, and policy- and education-oriented—and their effects on operating speeds and VRU safety are discussed separately. This type of research provides a foundation for future benefit-cost analyses and region-specific case studies. It also supports policymakers in designing and implementing more effective speed management strategies.

NON-INFRASTRUCTURE COUNTERMEASURES

This section explores operational, technological, and policy- and education-oriented non-infrastructure countermeasures and summarizes existing literature on their effects on operating speeds and VRU safety.

Operational Countermeasures

Operational strategies manage vehicle speeds by implementing enforcement (e.g., all kinds of speed cameras, police/patrol enforcement, and high-visibility enforcement), controlling traffic operations (e.g., speed limit settings, signal timing, and phase changing), and other strategies. These types of countermeasures regulate or optimize vehicle and pedestrian movements at specific locations, offering greater precision. In the short term, operational countermeasures are more flexible and effective, and are therefore commonly implemented by transportation agencies.

- **Speed Camera**

FHWA (2024) defines selection considerations for fixed speed cameras, point to point (P2P), and mobile cameras, as shown in Table 1. Speed cameras are found to reduce average speeds, speeding vehicle over PSLs, and speed-related crash counts. For example, Mountain et al. (2004) studied the effects of adding fixed speed-enforcement cameras at 62 sites on roads with severe speeding issues and a 30 mph PSL throughout the UK. After adding the cameras, average speeds at sites prior to the cameras fell 13.4% (from 32.8 mph to 28.4 mph), 85th percentile speeds fell 15.2% (from 38.9 mph to 33 mph) and the average share of vehicles exceeding the PSL fell from 64% to 29%. By using multiple cameras and detectors along a stretch of road, P2P camera systems extend the detection range and more accurately calculate the average speed of vehicles. Montella et al. (2015) analyzed the P2P cameras across seven study sections totaling11.2 miles on the urban A56 motorway in Italy, where PSL was 50 mph for light vehicles (weigh no more than 3.5 tons) and 45 mph for heavy vehicles. Based on over 22 million speed observations collected before and after enforcement, the team found that for light vehicles, average speeds decreased by 9.8% and 85th percentile speeds by 14.1%. For heavy vehicles, the reductions were smaller—average speeds declined by 4.8% and 85th percentile speeds by 8.4%. Additionally, the proportion of light vehicles exceeding PSLs dropped by 45%, and those exceeding PSLs by more than 6 mph fell by 72%, indicating that the P2P system is particularly effective in curbing excessive speeding. Unlike fixed and P2P speed cameras, which have limited sight distances and are site-specific, mobile units are portable and can be easily relocated. To investigate speed-related benefits of mobile speed cameras, Champness et al. (2005) conducted speed experiments at seven highway sites with a PSL of 62 mph. The results showed a significant reduction in speeds, with mean speeds decreasing by 3.7 mph and 85th percentile speeds by 4.3 mph. At camera sites, the percentage of vehicles exceeding the PSL dropped from 53% to 16%. However, these effects diminished just 0.9 miles downstream, suggesting that mobile speed cameras are effective in reducing speeds, but primarily within a limited range.

Table 1. Selection Considerations for Speed Cameras (Source: FHWA, Tab 1)

Considerations for Selection	**Fixed**	**P2P**	**Mobile**
Problems are long-term and site-specific.	X	X	
Problems are network-wide, & shift based on enforcement efforts.			X
Speeds at enforcement site vary largely from downstream sites.		X	X
Overt enforcement is legally required.	X	X	X
Sight distance for the enforcement unit is limited.	X	X	
Enforcement sites are multilane facilities.	X	X	

Beyond their role in reducing vehicle speeds and curbing speeding violations, speed cameras have also been found to be helpful in reducing crashes, injuries, and fatalities. De Pauw et al. (2014) conducted a before-and-after analysis on implementing fix speed cameras on a two-lane and a three-lane motorway in Belgium, where the PSL was 75 mph. Their study demonstrated a 37% decrease in motorcyclist and pedestrian casualties. Christie et al. (2003) also tested the effectiveness of mobile speed cameras at 101 sites across South Wales, UK. This study used circular zones with radii of 0.06, 0.19, 0.31, and 0.62 miles, as well as route-based covering the same distances in both directions. Among these sites, 76 had PSLs of 30 mph, 20 had PSLs of 60 to 70 mph, and the remaining 5 had PSLs of 40 to 50 mph. The safety impact of mobile speed cameras varied significantly based on the circular zone size and the distance from the enforcement sites. The study concluded that up to 78% of pedestrian-related injuries were prevented within 500 meters of the camera locations.

In real-world applications, permanent cameras exist in the US, mostly in New York City (NYC), Los Angeles, Chicago and many other big cities. As of January 2025, the NYC Department of Transportation (2024) has over 2,200-speed enforcement cameras in 750 school zones operating 24 hours a day, all year long. Vehicle owners are quickly alerted via email to each violation and assessed a $50 fine (typically paid online). This speed-management program has resulted in 94 percent fewer PSL violations since 2014. Likewise, the City of Portland, Oregon's Bureau of Transportation implemented a traffic safety program along key corridors in 2016 (FHWA, 2024) The city began with a 30-day warning period, during which speeding drivers received warning letters only. After this period, official citations with $160 fines for exceeding PSLs by more than 10 mph were issued by mail. The program resulted in 40% to 75% fewer PSL violations depending on location and 65% to 96% fewer drivers exceeding the PSL by more than 10 mph. Nowadays, Portland is still using these speed cameras as part of its Vision Zero initiative to eliminate fatalities and serious injuries.

- **Patrol Enforcement**

Stationary and mobile police enforcement are both widely used in patrol operations. In terms of their impacts on vehicle speeds, Armour (1986) investigated the impact of police presence on speeds along two-lane urban streets with a 37 mph PSL. The results revealed that police presence reduced the proportion of vehicles exceeding the PSL by up to 70%, and this effect lasted for at least two days after the enforcement was removed. In a longer-term operation, Walter et al. (2011) tracked speed changes during a four-week radar operation along a six-mile corridor on Highway A23 in South London. They observed a maximum decrease of 3.4 mph in average speeds at one site and a 4% to 9% reduction in drivers exceeding the PSL, with these reductions lasting for nearly two weeks at most locations.

Along with the studies on operating speeds, Nazif-Munoz et al. (2014) carried out a quantitative study on the impact of traffic law reform, police enforcement, and road infrastructure investment using data from 13 regions collected between 2000 and 2012. They developed structural equation models, considering traffic fatalities, severe injuries, and crashes as dependent variables. Additional variables, such as oil prices, alcohol consumption, the proportion of males aged 15-24 years old, and unemployment rates, were included as control variables. The findings indicated that the presence of police enforcement led to a 60% reduction in pedestrian fatalities and a 12.1% decrease in pedestrian crashes, making it significantly more effective than traffic law reform and road infrastructure investment.

- **Speed Limit Setting**

To manage vehicle speeds, strategies such as lowering PSLs, implementing variable speed limits (VSL), and adopting city-wide PSLs have been proposed as feasible and effective solutions. In practice, the U.S. and many European countries have been working for a long time to lower PSLs and, in turn, reduce the number of accidents and casualties. Elvik et al. (2004) conducted a meta-analysis of 98 studies, and the study found that when PSLs decreased by 5 mph, operating speeds dropped by 1 to 2 mph, indicating that the change in operating speeds was approximately 25% of the change in PSLs. Similar results were found in NCHRP 17-23. Researchers (Kockelman et al., 2006) tested the safety effects associated with a 10 mph increase in PSLs on high-speed roads, with PSLs of 55 mph and 65 mph, respectively and they found an average increase of 3 mph in driving speeds (30% of the added PSL). Common VSL strategies adjust PSL based on traffic conditions (congestion-responsive VSL) or weather conditions (weather-responsive VSL). The Wyoming Department of Transportation (WYDOT) (Buddemeyer et al., 2010) implemented a weather-responsive VSL system along the corridor which set PSL as 65 mph in the winter and 75 mph in the summer. Results indicated that when PSLs were reduced by 1 mph, drivers reduced their speeds by 0.47 to 0.75 mph. As one case of applying the same PSL to all roads, the Brussels-Capital Region (Brussels Times, 2021) introduced a region-wide 30 km/h speed limit for five months in 2021. Data collected by LiDAR cameras showed a 7% to 19% reduction in average speeds on all roads.

The effectiveness of these strategies in improving VRU safety is well-documented in several studies (Wong et al., 2005; European Data Journalism Network, 2023). A study by Waiz et al. (1983) examined car-pedestrian incidents in Zurich over a two-year period before and after lowering PSLs from 60 km/h to 50 km/h across the city. The analysis showed a 16% reduction in car-pedestrian injuries, a 20% decrease in pedestrian injuries, and a 25% decline in fatalities.

- **Traffic Operations**

Basic traffic signal timing plays an important role in managing traffic flow and protecting all road users. For instance, Safe Waves—a signal timing strategy that uses shorter cycles (66 seconds for AM peak and 84 seconds for PM peak), reduced coordination zones, pedestrian recall in areas with moderate pedestrian demand, undersized phases where demand is low, and adjusted offsets—was tested over three weekdays on a suburban arterial with a 40 mph posted speed limit in Danvers, MA (Furth et al., 2024). It proved effective in reducing the number of vehicles exceeding the speed limit by 79% overall.

In terms of pedestrian-specific signal timing, leading pedestrian intervals (LPIs) are designed to give pedestrian separately 3 to 7 seconds to enter the crosswalk before vehicles move. A study by Fayish and Gross (2010) evaluated the safety performance of 3-second LPIs at ten signalized intersections in downtown State College, Pennsylvania, where PSLs were 25 mph. The before-and-after analysis revealed that LPIs were effective in reducing 58.7% of pedestrian-vehicle crashes at the treatment sites. In addition to LPIs, protected left-turn phasing decreased pedestrian and cyclist crashes by 44.85% and 49.22%, respectively (Chen et al., 2013) and No Turn on Red (NTOR) (Joshua, 2022) could decrease the number of drivers failing to yield to pedestrians by 92%, leading to corresponding reductions in pedestrian crashes and injuries.

Table 2 ummarizes all existing literature examining the relationship between operational countermeasures and operating speeds. Speed cameras have significant effects in reducing operating speeds and speeding violations, with substantial research supporting these findings. On the other hand, traffic operation-related measures, such as signals and PSL settings, have a relatively minor impact on speeds and are less studied. Regarding VRU safety, Table 3 lists studies on the VRU safety impacts of operational countermeasures. It is found that operational countermeasures have a significant overall effect on improving pedestrian and cyclist safety. Among these, speed cameras, enforcement, and protected pedestrian signal changes (e.g., leading pedestrian intervals) are the most effective.

Table 2. Studies on the Relationship Between Operational Strategies and Operating Speeds

Study Description	**Method**	**Study Characteristic**	**Change in Travel Speed**
Speed Camera			
Mountain (2004) assessed the effect of 62 fixed speed cameras at various locations across the UK.	Before-after	• 30 mph PSLs	• Average speeds fell by 13.4% • 85th percentile speeds fell by 15.2% • % vehicles exceeding PSLs fell 35% points
De Pauw et al. (2014) investigated speed effects of fixed speed cameras on motorways in Belgium.	Before-after	• 75 mph PSLs	• Average speeds fell by 4 mph
Shin et al. (2009) analyzed the impact of a fixed camera program on one urban freeway in Scottsdale, AZ.	Generalized least square estimation	• 6.5-mile segment	• Average speeds fell by 12.3%
New York City (2024) examined the effectiveness of fixed cameras installed in 750 school zones.	Before-after	• $50 flat fine	• % vehicles exceeding PSLs fell by 94% since 2014
Portland BOT (FHWA, 2024) evaluated a fixed camera program along key corridors in 2016.	Before-after	• $160 fine for speeding 10+ mph over PSLs	• % vehicles exceeding PSLs fell 40% to 75% points • % vehicles speeding 10+ mph over PSLs fell 65% to 96% points
Montella et al. (2015) analyzed a P2P system on the urban motorway in Italy.	Before-after	• 50/43 mph PSLs for light/heavy	• Average speeds fell by 9.8% and 4.8% for light and heavy vehicles

		vehicles	• 85th percentile speeds fell by 14.1% and 8.4% for light and heavy vehicles
Ragnøy (2011) implemented P2P enforcement trials at three sites in Norway.	Before-after	• 50 mph PSLs	• Average speeds fell by 8.5%
De Pauw et al. (2014) examined the P2P enforcement at four locations on a three-lane motorway in Belgium.	Before-after	• 75 mph PSLs • 7.5-mile study segment for each location	• Average speeds fell by 4.8% • % vehicles exceeding PSLs fell 74% points • % vehicles speeding 10+ mph over PSLs fell 86% points
Champness et al. (2005) conducted speed experiments at seven highway sites.	Before-after	• 62 mph PSLs	• Average speeds fell by 3.7 mph • 85th percentile speeds fell by 4.3 mph • % vehicles exceeding PSLs fell 37% points
Patrol Enforcement			
Armour (1986) investigated speed impacts of police presence along two-lane urban streets.	Before-after	• 37 mph PSLs	• % vehicles exceeding PSLs fell 70% points
Walter et al. (2011) tracked speed changes along a 6-mile corridor on the highway in London.	Before-after		• 85th percentile speeds fell by 3.4 mph
Vaa (1997) experimented a 6-week police enforcement on a 21-mile road in Norway.	Before-after	• 37 to 50 mph PSLs	• Average speeds fell by 0.6 to 3 mph
Speed Limit Setting			
Switzerland (1996) decreased PSLs on motorways and examined the change of operating speeds.	Before-after	• PSLs decreased from 80 to 75 mph	• Average speeds fell by 3 mph
Elvik et al. (2004) explored the relationship between changes in operating speeds and PSLs.	Meta-analysis	• 98 studies • PSLs decreased by 5 mph	• Average speeds fell by 1 to 2 mph
Kockelman et al. (2006) tested safety impacts of PSL increases on high-speed roads.	Before-after	• PSLs increased from 65 to 75 mph and from 55 to 65 mph	• Average speeds rose by 3 mph
WYDOT (2010) examined speed effectiveness of one weather-responsive VSL system along the corridor.	Before-after	• 65/75 mph PSLs for winter/summer	• Average speeds fell by 4.7 to 7.5 mph in winter
Brussels Times (2021) assessed safety effects of a region-wide PSL settings for five months.	Before-after	• 19 mph PSLs	• Average speeds fell by 7% to 19%
Traffic Operations			
Furth et al. (2024) tested Safe Wavers for three weekdays periods on a suburban arterial in Danvers, MA.	Before-after	• 40 mph PSLs	• % vehicles exceeding PSLs fell up to 15% points

Table 3. Studies on VRU Safety Effectiveness of Operational Strategies

Study Description	Method	Study Characteristic	Safety Impact
Speed Camera			
De Pauw et al. (2014) investigated speed effects of fixed speed cameras on motorways in Belgium.	Before-after	• 75 mph PSLs	• Ped and cyclist deaths fell by 37%

Guerra et al. (2024) studied the effectiveness of eight fixed speed cameras installed along Roosevelt Boulevard in Philadelphia, PA.	Bayesian negative binomial and Poisson models	• 2018 to 2022 data	• Ped injuries rate fell by 1.83 times • Ped death rate fell by 2.53 times
Heiny et al. (2003) evaluated the SSC program on 17 segments in school zones in Seattle, WA.	Before-after	• 100 nearby segments included	• Ped and cyclist crashes fell by 18% at camera sites and by 5% nearby
Christie et al. (2003) tested the performance of mobile speed cameras at 101 sites across South Wales, UK.	Before-after	• Both circular zones and route	• Ped injuries fell by 78% within 0.3 miles
Patrol Enforcement			
Nazif-Munoz et al. (2014) carried out a study on the police enforcement in 13 regions in Chile.	Structural equation models	• 2000 to 2012 data	• Ped deaths fell by 60% • Ped crashes fell by 12.1%
Speed Limit Setting			
Waiz et al. (1983) examined the relationship between car-pedestrian incidents and lower PSLs in Zurich over two years.	Before-after	• PSLs decreased from 37 to 31 mph	• Ped deaths fell by 25% • Ped injuries fell by 20%
Brussels Times (2021) assessed safety effects of a region-wide PSL settings for five months.	Before-after	• 19 mph PSLs	• Ped injuries fell by 19%
Traffic Operations			
Fayish and Gross (2010) evaluated the safety performance of 3-second LPIs at ten signalized intersections in downtown State College, PA.	Empirical Bayes (EB) before-after	• 25 mph PSLs	• Ped crashes fell by 58.7%
Chen et al. (2013) evaluated protected left-turn phasing installed at 95 intersections in NYC.	Before-after	• 1990 to 2008 data	• Ped crashes fell by 44.85% • Cyclist crashes fell by 49.22%
Roshandeh et al. (2016) analyzed safety impacts of intersection signal timing optimization in CBD region.	Before-after	• 875 signalized intersections	• Ped crashes fell by 18%
Chen et al. (2013) evaluated the safety outcomes of increasing ped crossing time at 244 intersections in NYC.	Before-after	• 1990 to 2008 data	• Ped crashes fell by 50%
The District DOT (2022) tested the NTOR implementation in DC.	Before-after	• 74 locations	• Drivers failing to yield fell by 92%

Technological Countermeasures

Besides transportation agencies, manufacturers are actively integrating new safety-related features and designs into vehicles. Technologies such as intelligent speed assistance (ISA), automated emergency braking (AEB), and vehicle front-end geometry design are discussed in this section, focusing on their effectiveness in controlling operating speeds and ensuring pedestrian safety.

• ISA

ISA, as a speed-related alerting system for drivers, positively influences vehicles' effectiveness in curbing speeding. A study conducted by Várhelyi and Mäkinen (2001) on urban and rural roads to examine the effects of in-car speed limiters. These roads had PSLs ranging from 30 km/h to 120 km/h. Observations revealed that vehicle speeds decreased by 16.7% (5 to 10 mph) on roads with PSLs ranging from 30 km/h to 70 km/h. Figure 3 presented the observed mean speeds with and without speed limiter in a 60 km/h street in the city of Sabadell, Spain (all means normal driving conditions and free means driving unobstructed). It showed the obvious decrease in mean speeds with speed limiter in either driving conditions.

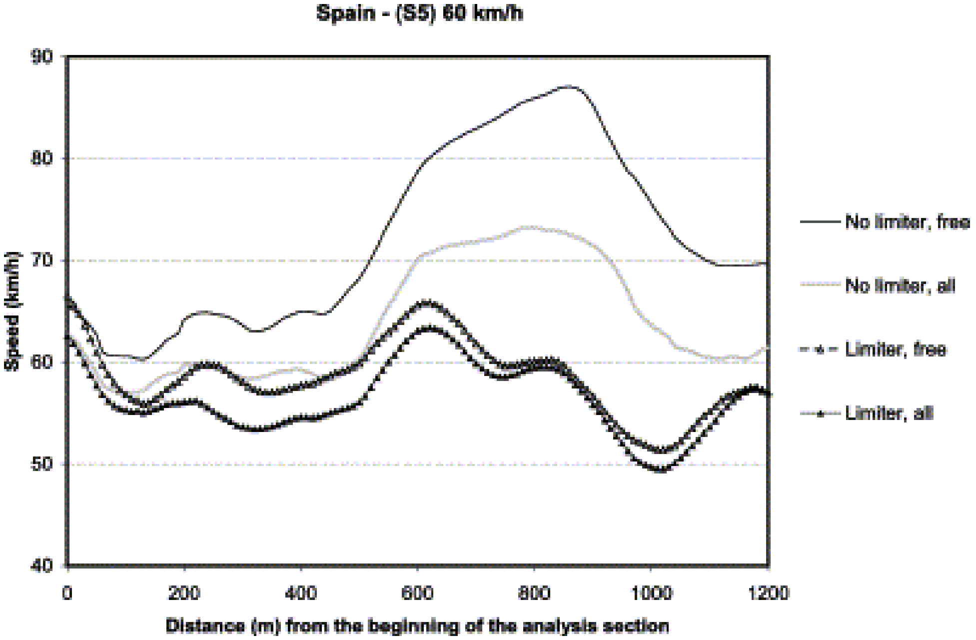

Figure 3: Mean Speeds with and without Speed Limiter

(Source: Várhelyi and Mäkinen, Fig 1 (2001)

By controlling speeds, ISA is also effective in reducing speeding-related crashes. According to Lai et al. (2012), the universal adoption of intervening ISA can reduce serious road traffic injuries by up to 29%. Different forms of ISA contribute to varying levels of accident reduction, and mandatory dynamic ISA has the most significant impact, potentially preventing 36% of injury accidents and 59% of fatal accidents (Carsten and Tate, 2005). Starting in July 2024, the European Union requires all newly launched vehicles to be equipped with ISA (European Commission, 2019).

- **AEB**

The AEB system detects potential collisions ahead and can automatically apply or assist in braking to prevent a crash. Cicchino (2022) conducted quasi-induced exposure analyses on police-reported crashes from 18 states between 2017 and 2020, accounting for drivers, vehicles, and environmental risk factors when evaluating the effects of AEB with pedestrian detection. The results showed that AEB reduced half of reported crashes, and pedestrian AEB was associated with a 27% reduction in pedestrian crashes. As a specific branch of AEB, the Pedestrian Crash Avoidance and Mitigation (PCAM) system, is designed to enhance pedestrian safety and reduce vehicle-pedestrian collisions. An experiment by Yanagisawa et al. (2014) evaluated the effectiveness of PCAM systems in preventing vehicle-pedestrian crashes through 900 tests involving three different light vehicles. The tests included various combinations of four scenarios, three pedestrian statuses (static, walking, running), four pedestrian movement directions (right-to-left, left-to-right, away, toward), four vehicle speeds (5, 10, 15, and 25 mph), and three obstruction time settings (none, 1300 ms, and 2700 ms). In the experiment, PCAM systems used detection sensors, radar, and cameras to alert drivers. The results showed that in the pedestrian running scenario, PCAM reduced pedestrian injuries by 11%, while in the walking scenario, injuries were reduced by 48%. Overall, the system demonstrated a 35% effectiveness in mitigating pedestrian injuries. These findings underscore the potential of advanced PCAM systems as an effective tool for improving pedestrian safety in the future.

- **Front-end Geometry Design**

Geometric design for vehicles, especially embedded safety-related features, is important for road users. Nie and Zhou (2016) examined the relationship between modifications in passenger car front-end geometry and the risk of serious injuries in pedestrian collisions. They compared the front-end designs of sedan and SUV models from 2008 to 2011 with those from before 2003, focusing on bottom depth and height. Their findings indicated that a flatter front-end design could reduce the risk of knee ligament injuries by 36.6% to 39.6%. In terms of specific details, Monfort et al. (2024) analyzed 121 pedestrian crashes between 2015 and 2021 to examine the relationship between vehicle design and pedestrian injury severity. The vehicles involved had an average speed of 45 km/h and an average model year of 2009. Using a Poisson model, the study found that vehicles with a lower leading edge height (less than 89 cm) were associated with a 28% reduction in pedestrian injury severity scores (ISS) compared to those with a higher leading edge height (greater than 89 cm). Additionally, vehicles with flatter bumper leads (<65°) had 34% lower pedestrian ISS than those with a bumper lead angle greater than 65°. Pedestrians struck by tall, blunt vehicles faced a higher risk of severe injuries to the torso and hip compared to other vehicle types. Besides, head injuries were more frequent and severe for pedestrians hit by tall vehicles, regardless of whether the front end was blunt or sloped, compared to shorter vehicles.

Among all technological countermeasures, ISA has been shown to reduce vehicle speeds (as listed in Table 4), while others remain uninvestigated. However, shown in Table 5, AEB and front-end geometry appear to have greater potential impacts on improving VRU safety. Due to limited research, however, the estimated reductions may be biased and require further assessment.

Table 4. Studies on the Impact of ISA on Vehicle Speeds

Study Description	**Method**	**Study Characteristic**	**Safety Impact**
Reagan et al. (2013) tested an auditory and visual advisory alerting system in Michigan.	Before-after	• 35 mph PSLs	• Time spent driving 1 to 4 mph over PSLs fell by 10%
Albert et al. (2007) evaluated speed benefits of equipping light goods vehicles with speed limiters.	Traffic simulation	• 62 and 75 mph speed limiters	• Average speeds fell by 10%
Várhelyi and Mäkinen (2001) examined the effects of in-car speed limiters on urban and rural roads.	Before-after	• 19 to 75 mph PSLs	• Average speeds fell by 16.7%

Table 5. Studies on VRU Safety Effectiveness of Technological Strategies

Study Description	**Method**	**Study Characteristic**	**Safety Impact**
ISA			

Fadel da Costa (2024) predicted the impact of ISA on traffic safety in 2030.	Safety impact calculation	• Unchanged accident type distribution	• Ped injuries fell by 0.6%
Ma et al. (2004) micro-simulated safety impacts of various ISA levels on three kinds of collisions — rear-end, vehicle-pedestrian, and intersection.	Before-after	• 18.6, 31, and 43.5 mph PSLs	• Ped injuries fell by 2% to 10% with 100% adoption • Ped death fell by 3% to 14% with 100% adoption
AEB			
Cicchino (2022) analyzed police-reported crashes from 18 states and evaluated effects of AEB on pedestrian safety.	Quasi-induced exposure analysis	• 2017 to 2020 data	• Ped crashes fell by 27%
Yanagisawa et al. (2014) tested the effectiveness of PCAM systems in reducing vehicle-pedestrian crashes.	Before-after	• 900 tests included	• Ped injuries fell by 35%
Mahdinia et al. (2022) assessed the impact of PCAM systems on pedestrian safety by using 3,095 field test data.	Regression model	• 2018 to 2021 data	• Ped crashes fell by 70%
Front-end Geometry Design			
Monfort et al. (2024) explored vehicle measurements' impact on ped injuries via 121 ped crashes.	Poisson model	• 2015 to 2021 data • 29 mph Speeds	• Ped injury severity score fell by 28% for <89 vs. >89 cm leading edge height • Ped injury severity score fell by 34% for <65° vs. >65° bumper lead angle

Policy- and Education-Oriented Countermeasures

Speed management is a collaborative effort involving governments, local communities, public campaigns, and citizens. This section discusses policy- and education-oriented countermeasures—including monetary incentives, Neighborhood Speed Watch programs, driver training, and other strategies—while exploring their feasibility in reducing speeding violations and protecting VRUs. Although most research has examined their effectiveness through small-scale pilot projects or simulator studies, these efforts still offer valuable insights into their feasibility and applicability.

To directly control driver behaviors, Reagan et al. (2013) tested a monetary incentive system in Michigan, involving a total of 50 participants over a 4-week period. Participants received an initial amount of $25, which decreased by 3¢ per 6 seconds for driving 5 to 8 mph over the PSL and 6¢ per 6 seconds for exceeding the PSL by 9 mph or more. Bonus amounts were visually displayed and updated in the assigned vehicles. Results revealed that the incentive system led to significant reductions in speeding. In 25 mph PSL zones, the average speed decreased by approximately 6.5% (1.6 to 1.8 mph), and the time spent driving above the PSL decreased by 11% to 13%. On the other hand, driver training has a longer-lasting effect (Brown et al., 2025). Crundall et al. (2010) examined the relationship between commentary training and driver performance using a driving simulator. The study divided 40 learners into two groups, and the experimental group received a classroom introduction in commentary training and a two-hour on-road training session. This work analyzed their behaviors (e.g., speed, braking) when encountering driving hazards. Observation results indicated that trained drivers responded to hazards more quickly and reduced their speed more significantly compared to untrained drivers. As teenagers are driving aggressively, many apps are also designed to help parents monitor their children's driving behavior and detect risky driving. The University of Minnesota (Creaser et al., 2015) developed the Teen Driver Support System (TDSS), which provides real-time feedback and also reports monitored behaviors to parents if risky driving persisted for a relatively long time. To assess its effectiveness, they divided 300 newly licensed teen drivers into three groups: control group (received no feedback), partial TDSS group (received in-vehicle feedback only), and full TDSS group (received both in-vehicle feedback and parental notifications). Final results over 52 weeks showed that the full TDSS group had the lowest percentage of miles spent speeding, reducing speeding by 7% compared to the control group and 2% compared to the partial TDSS group.

Campaigns and neighborhood programs encourage all possible road users and residents to enhance road safety. A one-month test conducted by Blume et al. (2000) assessed the effectiveness of the Neighborhood Speed Watch program in reducing speeds on two local roads in Massachusetts, with PSLs of 25 mph and 30 mph, respectively. Speed results on these two local roads, shows a 1 to 2 mph reduction in average speeds and a 5-mph reduction in 85th percentile speeds. Additionally, the percentage of vehicles exceeding the speed limit declined by 3.8% to 14.1% after the intervention. Few speed campaigns were adequately evaluated in terms of their impact on actual speed behaviors. For instance, Van Schagen et al. (2016) monitored speeds of 10 million vehicles over a 16-week anti-speeding campaign conducted at twenty locations in the Netherlands, with ten locations of 50 km/h PSLs and ten of 30 km/h PSLs. In this campaign, posters were placed at half of each group of locations to remind drivers of the speed limit. Results showed that average speeds on 30 km/h roads fell by 7.6 km/h with local posters installed.

So far, few studies have been conducted to examine the effectiveness of policies and education-related programs in improving VRU safety. DiMaggio and Li (2013) analyzed vehicle crash data from 2001 to 2010 in New York City and calculated annual pedestrian injury rates for different age groups, comparing periods with (between 2009 and 2010) and without (between 2001 and 2008) Safe Routes to School interventions during school hours. They found a 44% reduction in school-aged pedestrian injury rates, and the number of school-aged pedestrian injuries per 10,000 population decreased by 3.6. Along with SRTS program, Zegeer et al. ([i]) also investigated a comprehensive pedestrian safety program in Miami-Dade County. The study included four zones, with a total of 15,472 pedestrian-motor vehicle crashes analyzed over a nine-year period. This pedestrian safety program implemented 16 detailed countermeasures across educational, enforcement, and engineering categories in these four zones. Using a before period (1996 to 2001) and an after period (2002 to 2004), the analysis showed an 8.5% to 13.3% reduction in total pedestrian crash rates, and up to 18.5% reductions in child pedestrian crashes.

SUMMARY AND CONCLUSIONS

This paper reviews existing studies on non-physical countermeasures and summarizes their effectiveness, particularly in reducing operating speeds and enhancing safety for VRUs. While traditional physical countermeasures are well-evaluated using CMFs and benefit-cost analyses, non-physical strategies lack a comprehensive framework to guide researchers and practitioners. This literature review bridges this gap by providing a systematic overview to support future efforts in speed management.

However, new non-physical strategies for speed management continue to emerge and will be the focus of future work. For example, Li et al. (2024) proposed a smartphone-based approach with computer-vision-based speed estimation and vehicle identification (like vehicle make, model, and color, plus license plate reading). Several machine-learning approaches, including SVM, random forests, artificial neural networks, and time-series-based models, were tested to classify three speed cases: accelerating, decelerating, and maintaining constant speeds. All approaches yielded 90% to 95% accuracy in identifying speed changes among 188 cases. Although acoustic-based "cameras" (which "see" sounds to produce image for speed inference) are still under development to assist law enforcement, existing research suggests it is quite feasible. Of course, the legality of implementation (with standard cameras for vehicle identification) remains in doubt in many US states (GHSA, 2024).

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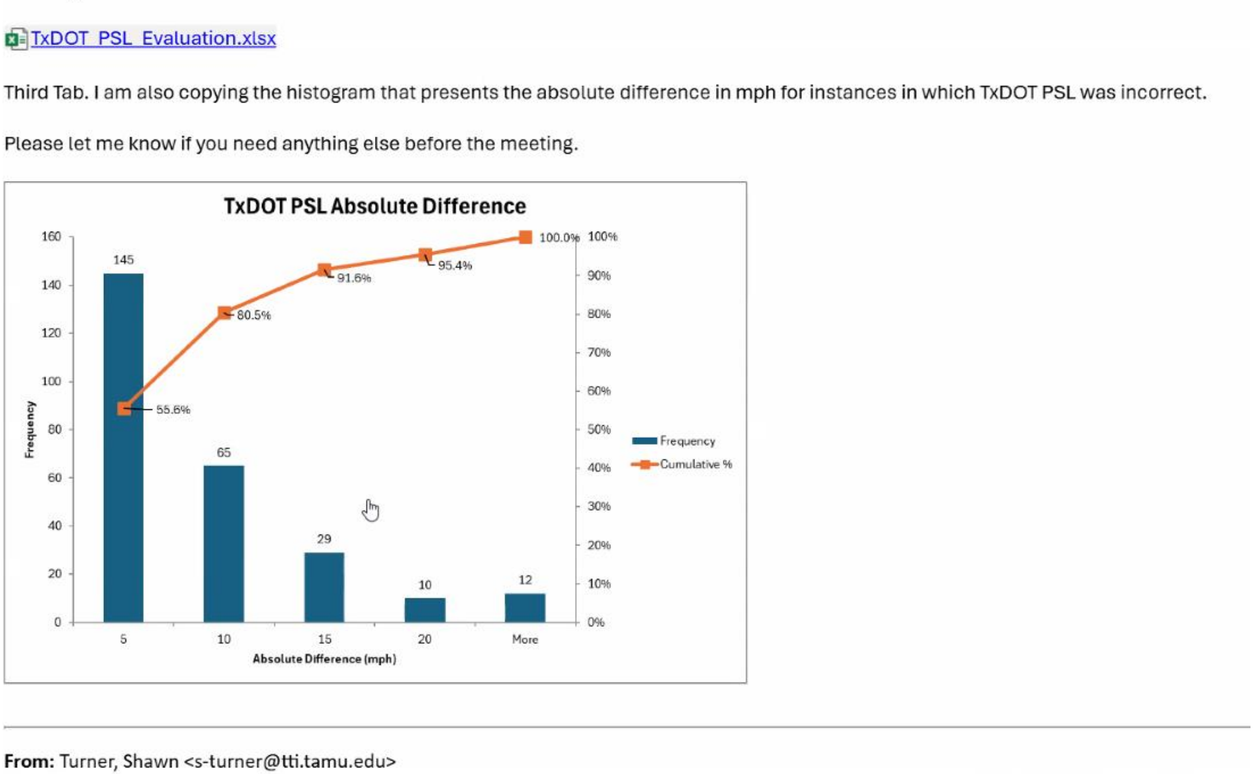
HIDDEN:

Notes from Dr. Shawn:

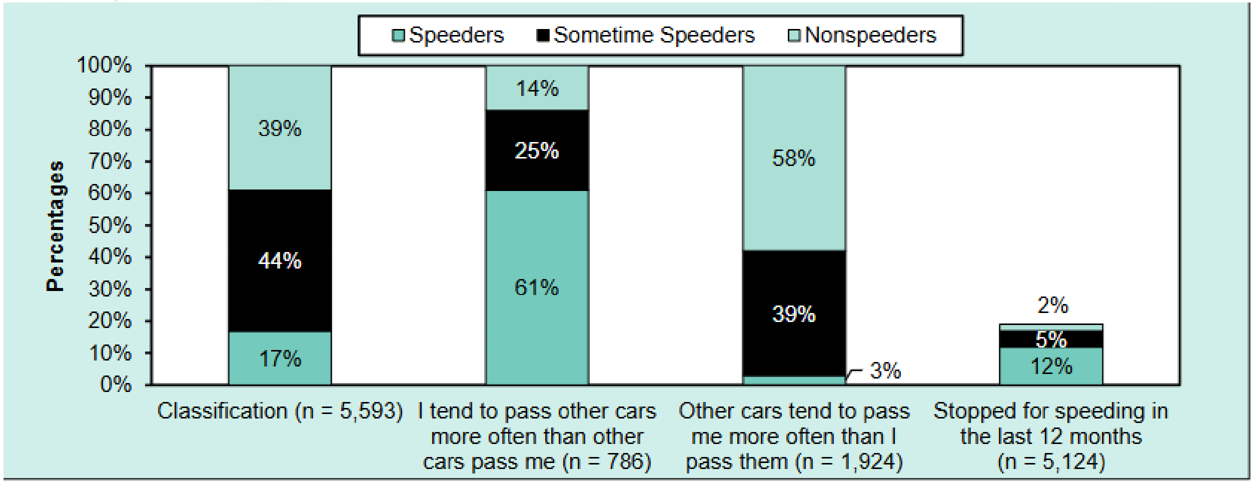


TxDOT_PSL_Evaluation.xlsx

Third Tab. I am also copying the histogram that presents the absolute difference in mph for instances in which TxDOT PSL was incorrect.

Please let me know if you need anything else before the meeting.

From: Turner, Shawn <s-turner@tti.tamu.edu>



https://rosap.ntl.bts.gov/view/dot/78929?utm_source=TRB+Weekly&utm_campaign=1f545c0b0f-EMAIL_CAMPAIGN_2025_01_14_02_40&utm_medium=email&utm_term=0_c66acb9bce-1f545c0b0f-532307022

Lane-Miles table: Table 3: Overview of TxDOT Roadway Inventory Dataset
(Source: TxDOT 2024)

TxDOT Road Classes	Interstate	Other Freeway & Expressway	Other Principal Arterial	Minor Arterial	Major Collector	Minor Collector	Local
Lane-Miles	36,150	17,097	71,778	52,287	107,742	31,998	437,791

% of Total Lane-Miles	4.8%	2.3%	9.5%	6.9%	14.3%	4.2%	58.0%
Posted Speed Limit (PSL) Distribution							
OSM Lane-Miles with >0 mph PSL	35,377	16,681	65,923	31,673	81,565	20,423	953
Lane-miles Weighted Average OSM or TxDOT?? PSL (mph)	68.86 mph	64.73 mph	57.55 mph	37.87 mph	44.95 mph	39.24 mph	0.11 mph