PRIORITIZING INVESTMENTS TO REDUCE VEHICLE-PEDESTRIAN CRASHES IN TEXAS

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ABSTRACT

When a vehicle collides with a pedestrian, the pedestrian will almost always be injured or killed, due to the extreme mass and materials differences. This paper investigates tvehicle-pedestrian crash records from Texas over 11 years (2009 to 2019) to propose and evaluate cost-effective treatments for reducing crash counts and severities. The deadliest corridors in Texas, where many such crashes were recorded, were identified, including many mid-block sites and unsignalized intersections. To reverse the trend, a total of 59 treatments, including speed limit reduction, added signage, and traffic signal changes, are worth considering. Among these treatments, 9 were applied to the most crash-prone segments and intersections, to deliver benefit-cost ratios, ranging from just 1.67 to a stunning 1,682.

KEYWORDS

Vehicle-Pedestrian Crashes, Benefit-Cost Ratios, Safety Treatments, Crash Modification Factors, Pedestrian Crash Reduction

INTRODUCTION

Across the US, police-recorded crashes on public roadways rose from 2.22M to 2.74M, between 2009 and 2019 (BTS, 2021). While just 2.7% of these involved pedestrians, nearly all pedestrian-involved crashes were labeled injurious (BTS, 2021). And roughly 17% of US crash deaths are pedestrians.

In order to save lives and avoid injuries while incentivizing more people to engage in active transport, in any nation, various safety strategies exist (Pantangi et al., 2021; Wu et al., 2020; Yue et al., 2020). Many treatments involve installation of physical facilities (Evstatiev et al., 2019; Yeo et al., 2020), while others rely on advertising campaigns, public policies, direct intervention, and/or regulation (Distefano & Leonardi, 2019; Job, 2020). Both strategy styles are known to enhance pedestrian safety, but benefit-cost comparisons of the basis of monetized impacts are very limited, in scope and number.

This paper quantifies and compares such treatments in order to prioritizes improvements for a variety of settings. Crash records (and police reports) were obtained from the Texas Department of Transportation's (TxDOT's) Crash Records Information System (TxDOT, 2021b). Several of the State's most dangerous segments and intersections are identified, and used as case studies for a series of benefit-cost ratio (BCR) comparisponsquantified.

LITERATURE REVIEW

Pedestrian crashes tend to be more severe in rural areas, due in part to higher speeds and lack of sidewalks and/or protective longitudinal barriers (including medians). Urban areas, by contrast, typically have lower speeds, more sidewalks, and denser street networks, leading to lower rates of pedestrian death per person-mile walked due to the lower speeds there (Stoker et al., 2015; Zegeer & Bushell, 2012). Data from Retting (2019) point to SUVs having a higher rate of involvement in US pedestrian crash fatalities in recent years, with a 50% increase in SUV-caused fatalities from 2009 to 2016, and a 7.9% year-over-year increase in SUV-caused fatalities from 2017 to 2018. According to (Retting, 2019), pedestrians struck by SUVs were about twice as likely to die as those struck by standard passenger cars, with significant increases in power-to-weight ratios at all vehicle weight benchmark percentiles. This result suggests that vehicles' design and safety measures are highly related to pedestrians' safety.

A pedestrian's age typically appears as the most practically significant factor affecting his/her road-crossing speed, thus increasing exposure to traffic while crossing. A study of crossing behavior in Utah found a slower walking speed among seniors, especially those with canes or walkers (Schultz et al., 2019). Furthermore, older adults are at a higher risk of death if they are involved in any given crash. A 2013 study found that in any given crash scenario, a 70-year-old that was hit is more likely to die associated with an 11.8 mph increase in speed, as compared to the equivalent crash for a 30-year-old (Tefft, 2013). Distracted driving, as well as distracted pedestrians, can be a significant factor in the prevalence of pedestrian crash injuries and fatalities. A study in Australia estimated that persons under 31 years of age have a higher-than-average propensity to be involved in mobile phone-related/-motivated crashes). The observations noted that pedestrians holding phones while crossing the street tended to cross more slowly, look around less, acknowledge others less, and look out towards vehicles less (Lennon et al., 2017).

Attitudes surrounding crossing at a crosswalk or crossing in the absence of a crosswalk are influenced by many factors, including gendera pedestrian's age and gender. A recent New Zealand study noted that 95% of that sparsely developed country's pedestrian fatalities took place at uncontrolled intersections and most of the population saw nothing wrong with crossing at a location lacking pedestrian infrastructure of any kind if it seemed safe to do so (Soathong et al., 2021). Average traffic speeds and speed limits play an outsized role in pedestrian crashes, and in particular, fatalities. After normalizing 2007–2009 risk levels, Tefft (2013) found that the median impact speed for injured pedestrians was 14 mph versus 35 mi/hr for pedestrian fatalities. The speed range at which the probability of a fatality increased most sharply lay between 25 to 40 mph, with about a 3% increase in the likelihood of a fatality for every 1 mph increase in speed. He estimated a pedestrian's fatality risk to be 90% when hit by a vehicle going 54.6 mi/hr (Tefft, 2013).

Past results suggest that pedestrian safety treatments should be attempted in various sites and setting, including construction of new facilities, education, traffic operations, and vehicle design. So this paper investigates the payback on such investments.

DATA ANALYSIS

Pedestrian crash records analyzed here come from TxDOT's Crash Records Information System (CRIS) online database (TxDOT, 2021b). Between January 2009 and December 2019, 57,832 vehicle-pedestrian crashes were reported (to police) and then recorded (by police). 12.9% of these crashes occurred at signalized intersections, 16.1% were at unsignalized intersections, and 71.0% were in between intersections/along corridors. 9.1% of these crashes involved one person being killed, 16.8% led to an incapacitating injury, 33.2% resulted in a non-incapacitating injury, 28.4% had a possible injury, 12.0% had property damage only, and 0.4% of outcomes were unknown. Among the fatal crashes (anyone killed), 3.8% occurred at signalized intersections, 7.6% at unsignalized intersections, and 88.6% occurred in between intersections/along corridors.

71.0% of Texas' pedestrian crashes and 88.6% of its fatal pedestrian crashes occurred along corridors, and in between intersections. While one may wish to build fences everywhere, such treatments can be quite expensive and unrealistic, since motorists may find themselves trapped (after a vehicle disabling event, for example) and unable to park (and walk to their destination). Haleem et al. (Haleem et al., 2015) observed that pedestrians are more vulnerable at unsignalized intersections than signalized intersections, especially if the pedestrian is at fault (e.g., crossing without crosswalk). Crash cost assumptions used here come from TxDOT's (2021a) recent Highway Safety Improvement Program manual, with average comprehensive costs (including quality-of-life costs and lost productivity) of $500,000 for non-incapacitating injury crashes and $3.5 million for each incapacitating or fatal crash.

As shown in Figure 1, vehicle-pedestrian crashes peak twice a day in the State of Texas (and probably most places): around 7 to 9 AM (with the morning rush hours) and 4 to 10 PM (with afternoon rush hours and activities after dark). Since most of Texas' fatal pedestrian crashes occur under unlighted, nighttime conditions, it may be reasonable to improve signage and streetlighting, while also adopting lower speed limits and more stringent regulations on driving under the influence (DUI).

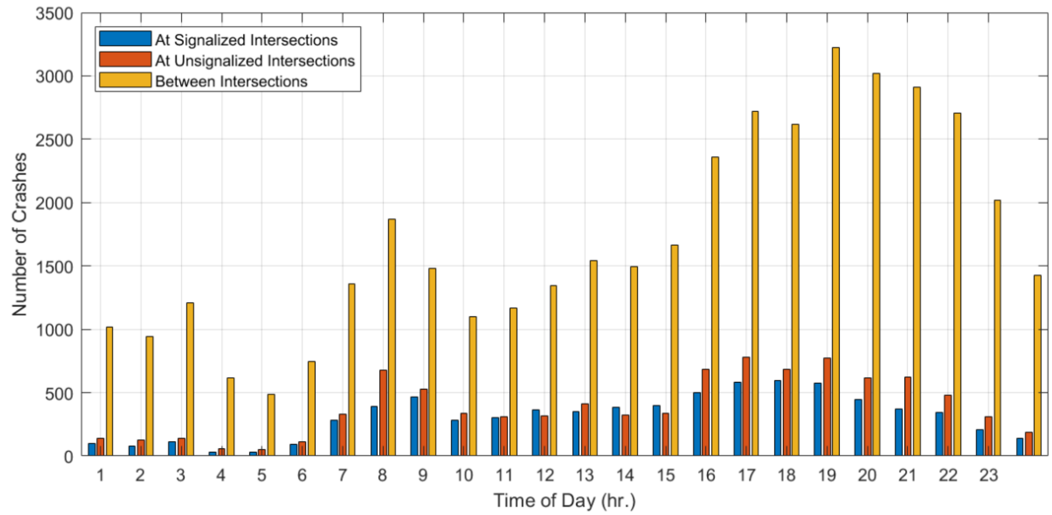

Figure 1. Vehicle-Pedestrian Crashes by Time-of-Day

By month of year, **Figure 1**Figure 2**Error! Reference source not found.** shows vehicle-pedestrian crashes tend to fall in the summer season and increase in the winter season for all three cases. Summer season, from June to August, has the fewest crashes, presumably due to having more daylight hours. The hot weather conditions in Texas may have reduced the number of pedestrians walking along the sidewalk, leading to reduced vehicle-ped crashes during summer months. Autumn season from September to November is the most vulnerable season for pedestrians, having the highest crash counts. This may be because the sun sets earlier in the Fall (as children return to school), bringing shorter days and fewer daylight hours, with crash counts rising from September to November. Therefore, treatments related to weather conditions (e.g., road pavement improvements and streetlights) may be a good option if seasonal changes are critical factors in crash occurrences.

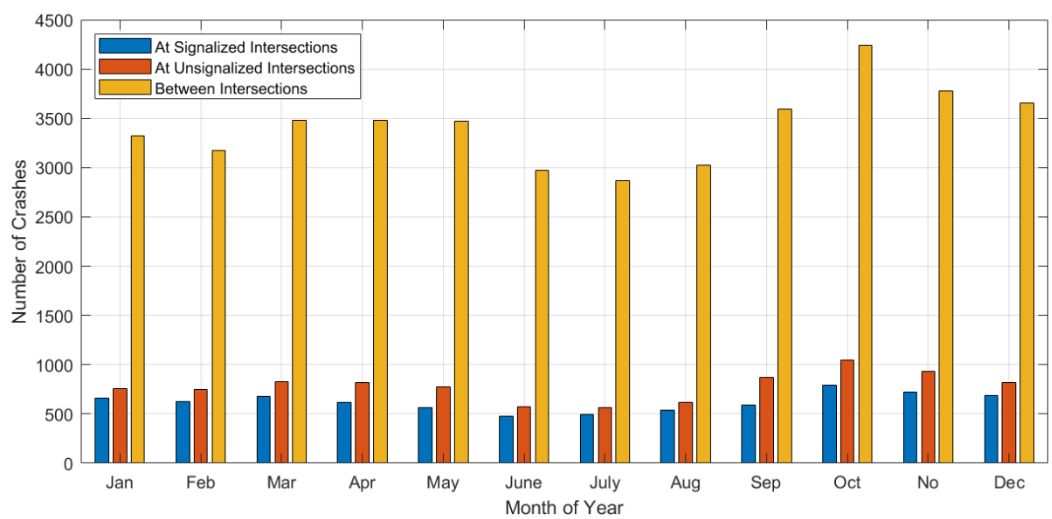

Figure 2. Texas' Pedestrian Crashes by Month, in Years 2009 – 2019 (TxDOT)

Figure 3**Figure 3** shows the spatial distribution of vehicle-ped crash occurrences in intersections around Texas. Most crashes occurred in and around the state's largest cities (Austin, Dallas-Fort Worth, Houston, and San Antonio). However, several crashes are also observed near the border of Texas and Mexico, presumably because of the high pedestrian volumes in some border communities and high truck traffic crossings the border. Signalized intersection crashes tend to occur more often in city centers (where signals are most common), while unsignalized intersection crashes can be found across all settings.

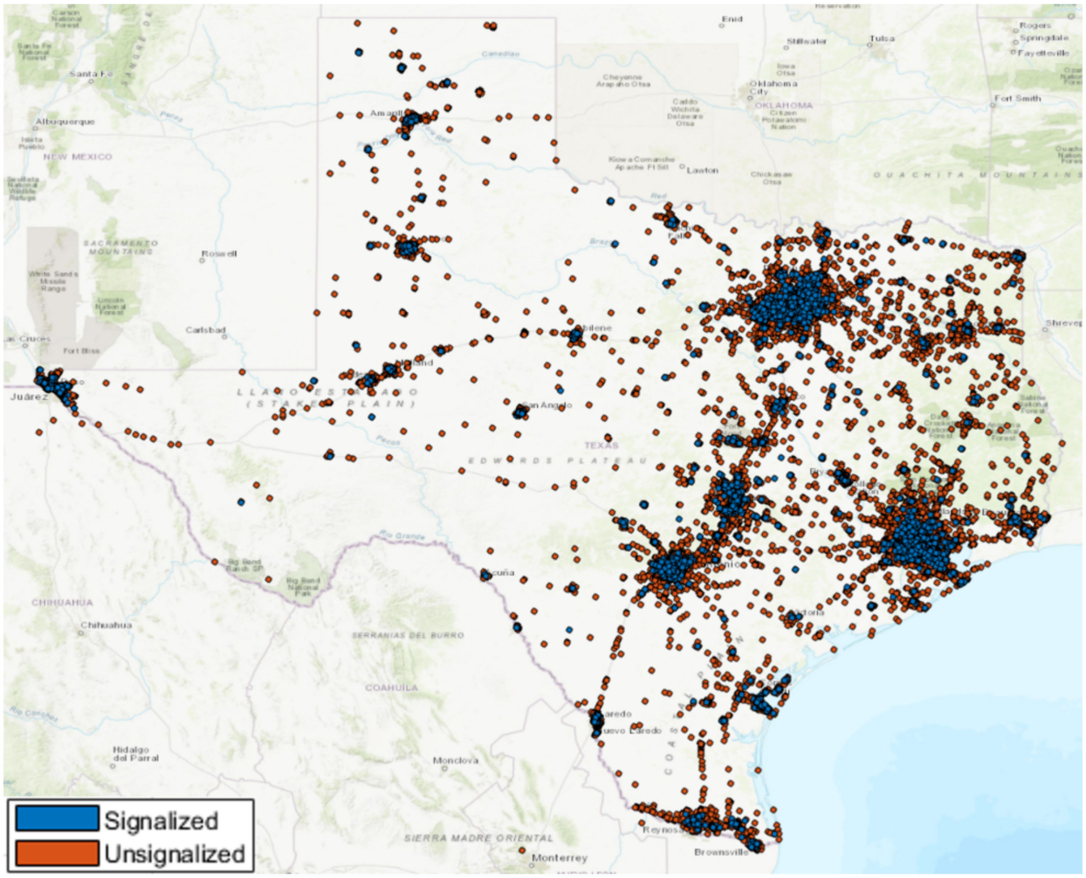

Figure 3. Pedestrian Crash Locations across Texas (Years 2009-2019)

Figure 4 shows crash locations by injury severity. The crashes that occurred near urban regions are likely to result in mixed severities ranging from ‘killed’ to ‘not injured’. However, crashes in the rural regions are likely to be more fatal than crashes in urban regions. This may be due to rural regions’ high vehicle speeds. Therefore, speed reduction and enforcement can be attempted in rural regions to reduce injury severity resulting from vehicle-pedestrian crashes.

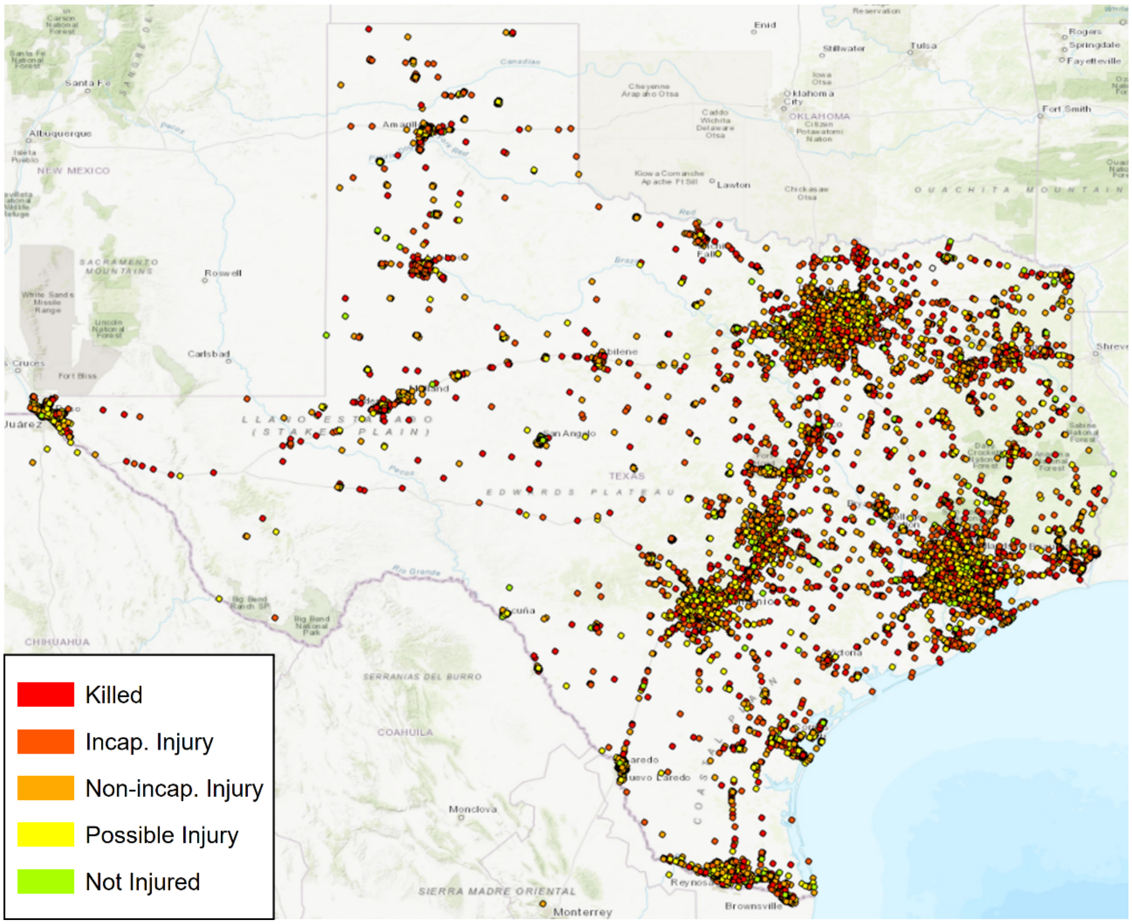

Figure 4. Severity versus Location of Texas Crashes (Years 2009-2019)

Benefit-Cost Analysis (BCA)

BCRs reflect anticipated reductions in crash costs over coming years multiplied by a treatment's crash modification factor (CMF), divided by the sum of countermeasure implementation costs. The BCRs developed here, via a benefit-cost analysis (BCA) and the associated CMFs rely on several underlying assumptions. For benefit computations, CMFs come primarily from U.S. CMF Clearinghouse and the UNC Highway Safety Research Center's 2013 report on CMFs (Bushell et al., 2013). Equation 1 shows how the BCR is calculated.

$$BCR = \frac{\sum_i \sum_t \frac{B_{ijt}}{(1+d)^t}}{\sum_i \sum_t \frac{C_{ijt}}{(1+d)^t}} \tag{1}$$

$$B_{ijt} = Crash_{ijt}(1 - CMF_j)$$

$$C_{ijt} = Treatment\ Cost_{ijt} + Delay_{ijt}$$

where i = crash location, j= treatment type, t=year of the crash, d= discount rate, B_{ijt}=benefit of treatment j at location i at year t, $Crash_{ijt}$= crash cost of ijt, CMF_j=crash modification factor of treatment j, $Delay_{ijt}$=delay cost (if applicable) of adopting treatment j at location i at year t, and C_{ijt}=sum of crash cost and delay cost due to the treatment j.

Unfortunately, some benefits are difficult to measure, such as mode shifts from private cars to walking or other active modes (because of improved pedestrian safety) and any associated improvements in human health, greenhouse gas emissions and air and water quality. These additional benefits are left out of this paper's calculations but may offer meaningful benefits. This work does rely on a $16.20-per-vehicle-hour value of travel time (US DOT, 2022) and a discount rate (*d*) of 8% to discount 10 years of future delay costs to nearby motorists – if they are slowed by some of the treatments (since reduced speed or advanced pedestrian crossing are important treatment options). Here, the average delay for leading pedestrian intervals (at signalized crossings) or removal of right turn permissions on red are assumed to be 1 second per vehicle (for all through and turning vehicles) and 10 seconds per right-turning vehicle, respectively.

Treatments to Reduce Pedestrian Crashes

The treatments to reduce pedestrian crashes are obtained from a variety of sources across the internet and highway safety manuals, including the crash modification factor (CMF) Clearinghouse (Crash Modification Factors (CMFs) Clearinghouse, 2021), and the report by the UNC Highway Safety Research Center by (Bushell et al., 2013). The list of treatments is delivered in 5 categories, arranged by the general purpose of the treatment, as well as the roadway users primarily affected by the treatment.

The treatments shown in Table 1 involve adding treatments to the roadway that do not affect the material roadway conditions for drivers. For the most part, these treatments include enhanced signage, and attention-getting measures such as the rectangular red flashing beacon and pedestrian-hybrid beacons. These treatments can typically be applied at the corridor level along corridors experiencing high crash count. The treatments shown here do not require much construction effort. For instance, prohibition of right-turn on red (RTOR) is primarily involved to add treatments to the roadway that do not affect the material roadway conditions for drivers. It can increase drivers' delays but lead to positive outcomes in pedestrian safety.

Table 1. Basic Roadway Treatments

Treatment	Cost (average)	Cost Unit	Avg. CMF
Basic curb	$21	Linear Foot	0.89
Basic curb and gutter	$21	Linear Foot	0.89
"Daylighting" Left Turns & Crossing Locations	$300	Each	0.75
Gateway signage (see examples)	$22,750	Sign + Structure (each)	0.83
Narrowed curb radii	$32,500	Per corner	0.81
Pedestrian-hybrid Beacons	$57,560	Each	0.71
Prohibition of left turns	$800	Per sign	0.28
Prohibition of right turn on red	$800	Per sign	0.77
Crosswalk (Hi-vis; see citation for specs)	$2,540	Each	0.63
Raised Crosswalk	$18,995	Each	0.64
Flashing Beacon	$10,010	Each	0.85
Rectangular Red Flashing Beacon (RRFB)	$22,250	Each	0.53
Raised Center Medians (Uncontrolled)	$7.26	Square Foot	0.93
Barriers Installed on Top of Concrete Median	$210,000	Per mile	0.63
Advanced Stop/Yield Sign	$520	Each	0.75
Install Crosswalk Sign	$570	Each	0.91

Narrow Roadway from 4 Lanes to Three Lanes	$20,000	Per Mile	0.71

The treatments shown in Table 2 are generally related to traffic calming measures, reducing vehicle speed. As speed is a major factor in pedestrian crashes that involve fatalities (Bernhardt & Kockelman, 2021; Tefft, 2013), these treatments seek to limit the impact of speed and narrow the roadway so that pedestrians have less exposure time when crossing. While the cost of implementing these treatments varies widely, from roadway reconfiguration to simple signage, their impacts can be significant when implemented in areas with high pedestrian traffic. For the impact area of speed limit reduction on the intersection, 500 ft is assumed to be affected by the speed limit reduction near the intersection, and the vehicles' delay costs are added to the overall cost of the treatment.

Table 2. Traffic Calming Treatments

Treatment	**Cost (average)**	**Cost Unit**	**Average CMF**
Speed Humps	$2,640	Each	0.64
Speed Limit Reductions - 15% decrease	$135	Each (sign)	0.89
Speed Limit Reductions - 10% decrease	$135	Each (sign)	0.79
Speed Limit Reductions - 5% decrease	$135	Each (sign)	0.705
Chicanes	$9,960	Each	0.69
Diverters	$26,040	Each	0.69
Curb Extensions (bulb-outs)	$13,000	Each	0.75
Traffic circle	$85,370	Each	0.75
Road Diet	$40,000	per mile	0.71
Hardened left turns	$2,500.00	Each	0.65

The treatments shown in Table 3 are related to the addition of infrastructure that tends to pedestrian needs, ranging from signage to barriers and signal improvements. A few of these treatments can limit pedestrian contact with vehicles altogether, such as pedestrian bridges, but these are typically very high cost. Additionally, traffic signals can help provide a controlled crossing at an intersection where a treatment such as a pedestrian-hybrid beacon would not be appropriate, and some of these treatments also have crossover safety improvements with drivers. Treatments such as signal re-timings, leading intervals and scramble intervals can increase driver delays, but lead to positive outcomes in pedestrian safety.

Table 3. Pedestrian-specific Infrastructure

Treatment	**Cost (average)**	**Cost Unit**	**Average CMF**
Streetlight	$4,880	Each	0.44
In-pavement lighting (flashing crosswalks)	$17,260	Complete system*	0.71
Pedestrian Leading Intervals	$1,750		0.85
Crosswalk Signage (for road users)	$30	Square Foot	0.84
Bollards (at crossing points)	$730	Each	0.93
Curb Ramps (to crossings)	$810	Each	0.95

Pedestrian Refuge Islands	$10	Square Foot	0.44
Fence (general purpose)	$130	Linear Foot	0.63
Pedestrian overpass (wooden)	$124,670	Each	0.63
Pedestrian overpass (steel)	$206,290	Each	0.63
Pedestrian underpasses		Square Foot	0.63
Sidewalk railings	$100	Linear Foot	0.83
Access management improvements (esp. at commercial centers)	$4,000	Per Driveway removed	0.5
Ped Detection - Detector (actuate)	$390	Each	0.55
Ped Detection - Push Button	$350	Each	0.83
Audible Pedestrian Signal*	$800	Each	0.72
Increase Crossing Time		Per re-timing	0.49
Countdown timers	$740	Each	0.48
Pedestrian signal (complete)	$3,260	Each	0.6
Traffic signal (new)	$90,000	Each	0.44
Dedicated pedestrian interval	$1,750	Per re-timing	0.41
Speed trailers	$9,510	Each	0.95

The treatments shown in Table 4 are related to street furniture. Street furniture is another potential option that can help with traffic calming and provide additional services to pedestrians. As studies on crash reduction effects are limited, these estimates are provided by (Bushell et al., 2013). These treatments can also indicate to drivers that they are entering into a crowded area, or one with high pedestrian activity, and drivers are more likely to reduce their speed, improving pedestrian safety outcomes (Bushell et al., 2013).

Table 4. Street Furniture Treatments

Treatment	Cost (average)	Cost Unit	Average CMF
Street trees	$430	Each	0.82
Bench	$1,550	Each	0.82
Bus shelter	$11,560	Each	0.82
Trash/recycling receptacle	$1,420	Each	0.82

The addition of sidewalks in areas where they do not currently exist, as shown in Table 5, is among the most basic treatments available to improve pedestrian safety. While grade separation can be costly, even providing a basic sidewalk can lead to reductions in crashes by 75% or more (Crash Modification Factors (CMFs) Clearinghouse, 2021).

Table 5. New Sidewalk Infrastructure Treatment

Treatment	Cost (average)	Cost Unit	Average CMF
Widen paved shoulder	$5.56	Square Foot	0.72
Asphalt Sidewalk	$35.00	Linear Foot	0.26

Concrete sidewalk	$32	Linear Foot	0.26
Concrete sidewalk w/curb	$150	Linear Foot	0.26
Multi-use trail - paved	$481,140	Mile	0.14
Multi-use trail - unpaved	$121,390	Mile	0.14

Policy treatments can cause behavioral changes in roadway users and can affect various areas, including traffic patterns, geometry, and enforcement. For instance, due to children hesitating to walk/bike to school and the potential risk of death or injury for pedestrians and bikers, California implemented the Safe Routes to School (SR2S) program and authorized issuance of a competitive grant process for roadway construction projects (Gutierrez et al., 2008). This program is estimated to reduce 13% of crashes by the CMF being 0.87. However, legislative treatments should be implemented in large scale and for a long period of time. Policy treatments should be considered a long-term preventative method to gradually transform society's structure, in combination with other treatments introduced in this paper to improve pedestrian safety.

Table 6. Policy and Legislation

Treatment	**Cost (average)**	**Cost Unit**	**Average CMF**
Implement Safe Routes to School Program	$190 million	California Statewide	0.87

Benefit Cost Ratio (BCR) Results

Deadliest Corridors in Texas

The intersections and 0.1-mile segments are derived from OpenStreetMap, and selected crash records are then used as inputs for a process of building up analysis corridors. The algorithm for performing this follows a "greedy" pattern of picking up the worst intersections first and building off of them. The next worst intersection, in terms of the number of pedestrian-related crashes, is picked in this pattern. For each cross street, the algorithm will "walk" down each direction of eligible 0.1-mile segments from the starting intersection until 3 successive segments and intersections that coincide with them each have fewer than 5 pedestrian-related crashes, or the end of the street is reached. All segments and intersections that traversed as a new corridor are recorded. Cumulative KABCO scores are included for all of the ped crashes therein, and make those segments ineligible for inclusion in future corridors. Based on the described selection method, Table 7 shows a comprehensive ranking of the 10 most dangerous corridors based on pedestrian crash frequency and crash costs across the State of Texas.

Table 7. Deadliest Corridors in Texas

Ranking	**Corridor Name**
1	I-35 Southbound Frontage Road – Martin Luther King Jr. Blvd. to Holly Street (Austin)
2	Tomball Parkway (SH-249) – Sam Houston Tollway (SL-8) to Breen Road (Houston)
3	Westheimer Road – Fondren Road to Chimney Rock Road (Houston)
4	Congress Ave. – 12th St. to Barton Springs Road (Austin)
5	Lamar Blvd. – Masterson Pass to Payton Gin Road (Austin)
6	Congress Ave. – Woodward St. to St. Elmo Road (Austin)
7	E. Riverside Drive – Pleasant Valley Road to Faro Dr. (Austin)

8	Zarzamora Street – Cincinnati St. to Delgado St. (San Antonio)
9	Fannin Street – Commerce St. to Jefferson St. (Houston)
10	Milam Street – McGowan St. to Alabama St. (Houston)

A total of 8 treatments are chosen to be applied to the vulnerable intersections or segments that are included in the deadliest corridors in Texas. The detailed calculation results of the BCRs can be found in the Appendix. The treatments shown in Table 8 require construction of additional transportation infrastructure or facilities. These treatments do not induce traffic delays, so that relatively low-cost results in high BCR compared to other treatments to be discussed in this paper.

Table 8. BCRs of Treatments requiring Constructions

Treatment	Location	BCR
Advanced Stop/Yield Sign (20 signs)	Tomball Parkway (Fallbrook Dr. to Bammel Rd., Houston)	1682
	Westheimer Road (Fondren Road to Chimney Rock Road, Houston)	1598
	I-35 SB Frontage Road & 7th Street (Austin)	1522
Pedestrian Refuge Islands	Rundberg Lane and Lamar Boulevard (Austin)	653
	Payton Gin Road and Lamar Boulevard (Austin)	908
Barriers installed on top of concrete median	I-35 Freeway Main lanes (Austin)	25.96

Table 9 shows the treatments related to installing new traffic signal systems or adjusting signal timing. A direct difference compared to the treatments from Table 8 is that the changes in traffic signals will cause traffic delay costs to increase. This results in relatively higher cost for the treatment, resulting in relatively lower BCRs in Table 9 compared to the results from Table 8.

Table 9. BCRs with Treatments Related to Signals

Treatment	Location	BCR
Prohibit Right-turn on Red	Congress Avenue and Cesar Chavez Street (Austin)	5.38
	Congress Avenue and 6th street (Austin)	4.15
Pedestrian-Hybrid Beacons (4 Beacons)	Tomball Parkway (Fallbrook Drive to Bammel Road, Houston)	11.57
	Westheimer Road (Fondren Road to Chimney Rock Road, Houston)	3.16
Pedestrian Leading Interval	6th street and I-35 SB Frontage Road (Austin)	2.34
	Congress Avenue and 6th Street (Austin)	2.76
	East Riverside Drive and Wickersham Lane (Austin)	2.97

	Zarzamora Street and Culebra Road (San Antonio)	21.13
	Fannin Street and Walker Street (Houston)	8.79
	Fannin Street and Congress Street (Houston)	5.38

Table 10 shows the results from reducing the speed limit, which is a more direct treatment. Reduced speed limit (of 10%) will directly improve safety conditions, since speed is considered as a major factor in pedestrian crashes (Bernhardt & Kockelman, 2021; Tefft, 2013). However, speed limit reduction will increase the delay costs even more than adjusting traffic signal systems. Therefore, it is recommended to consider reducing the speed limit as the least favorable choice among the other treatments.

Table 10. BCRs with Treatments Related to Speed Reduction

Treatment	Location	BCR
Speed limit 10% reduction	Tomball Parkway (Houston)	1.67
	Westheimer Road (Houston)	2.40
	Congress Avenue (Austin)	3.92
	East Riverside Drive and Pleasant Valley Road (Austin)	2.40

Lastly, traffic calming methods are considered in Table 11. Traffic calming is a treatment that reduces the speed limit but can be applied at a place where high pedestrian volume can be expected. Here, road diet is applied to the downtown Houston area, where the volume of both pedestrians and vehicles are expected to be high. The lanes that are no longer operational as a result of road diet can be used to install pedestrian facilities (e.g., sidewalks), so that additional improvements to pedestrian safety can be expected as well.

Table 11. BCRs with Treatments Related to Traffic Calming

Treatment	Location	BCR
Road Diet	Milam Street (from McGowan Steet to Alabama Street, Houston)	3.03

Crash Severity Classification and Benefit Cost Ratios

With the 52,837 crash records in the last 10 years and the list of treatments applied to the deadliest corridors in Texas, this paper developed a crash severity classification algorithm using support-vector machine (SVM) and prioritized treatments by benefit cost ratio. SVM is a type of supervised learning model specialized in regression and classification problems (Cortes & Vapnik, 1995). Here, the 51,824 crash records are labeled by their crash severity following the KABCO scores, and the 10 attributes of the crash details are defined as shown in Table 12. 1,013 crash records out of the total 52,837 in the data set were excluded since their crash locations were not precisely labeled (location type being “other”). The SVM classifier developed in this paper classifies crashes in three different classes with their corresponding KABCO scores in parenthesis as: high risk (KA), medium risk (B), and low risk (CO). With the proposed SVM approach, each crash record can be categorized with its most likely crash severity after considering the crash attributes.

Table 12. Attributes used for Crash Severity Classification

Attributes	Description
Month of Crash	Month when the crash occurred. [January, February, March, …, November, December]
Time of Crash	Time of day when the crash occurred. [0, 1, …, 22, 23 in hours]
Collision Type	Type of collision in regard to vehicles or pedestrians. [Single vehicle accident, Two vehicles angled accident, Two vehicles same direction accident, Two vehicles opposite direction accident, Other]
Location Type	Type of location where the crash occurred. [In between intersections/along corridors, Signalized intersection, Unsignalized intersection]
Traffic Control	Type of traffic control where the crash occurred. [Signalized, Unsignalized, Other]
Light Condition	Light condition when the crash occurred. [Dark-unknown lighting, Dark - lighted, Dusk, Dawn, Daylight, Other]
Weather Condition	Weather condition when the crash occurred. [Clear, Cloudy, Rain, Sleet/hail, Snow, Fog, Blowing sand/snow, Severe crosswinds, Unknown, Other]
Speed Limit	Speed limit of the location where the crash occurred. [From 5 to 85 in mph]
Crash Fatality	Indicator that the crash involved one or more fatalities [Yes, No]
Pedestrian Injury	Indicator that pedestrian was injured or not [Yes, No]

This paper used the SVM model provided in the 'sklearn' Python library with default settings for its parameters. Among the four different kernels including linear, poly, radial basis function, and sigmoid, the linear kernel was chosen for SVM due to its best performance in mean average error (MAE). By comparing the crash cost of observed crash severity versus predicted crash severity, linear kernel had the lowest MAE of $680,310 per crash. This represents that the proposed SVM classifier was able to predict crash severity with less than one level difference in KABCO score.

After each of the crash records were re-classified by their predicted crash severity, a total of 8 different treatments – the same treatments applied to the deadliest corridors in Texas – were applied to each crash record, and their benefit-cost ratios were measured. Depending on the type of crash, some treatments cannot be applied due to the crash's geographical features. For instance, barriers cannot be installed in the middle of an intersection, only along the corridors, and prohibiting right-turn on red cannot be applied to unsignalized intersections. Considering the locational features of the crashes, Table 13 shows the predicted crash severity, types of treatments, sample size, and its average and standard deviation of benefit-cost ratio.

Table 13. Treatments and Avg. BCRs by Predicted Crash Severity and Location

Predicted Crash Severity	Crash Location (sample size)	Treatment	Avg. BCR (Std.)
High risk	In between intersections/along corridors (n=4,588)	Barriers Installed on Top of Concrete Median	4.54 (7.05)
		Pedestrian-hybrid Beacons	3.41 (9.54)
		Road Diet	1.35 (8.99)

		Speed Limit Reductions - 10% decrease	0.45 (3.04)
	Unsignalized Intersection (n=150)	Pedestrian Refuge Islands	2051.44 (2579.26)
		Advanced Stop/Yield Sign	112.98 (142.05)
	Signalized Intersection (n=203)	Pedestrian Refuge Islands	1759.30 (1700.30)
		Pedestrian Leading Intervals	1.50 (1.31)
		Prohibit Right-turn on Red	0.23 (0.20)
Medium risk	In between intersections/along corridors (n=31,626)	Barriers Installed on Top of Concrete Median	1.89 (6.03)
		Pedestrian-hybrid Beacons	1.87 (7.27)
		Road Diet	0.69 (7.73)
		Speed Limit Reductions - 10% decrease	0.23 (2.67)
	Unsignalized Intersection (n=3,351)	Pedestrian Refuge Islands	585.48 (2554.18)
		Advanced Stop/Yield Sign	46.14 (173.65)
	Signalized Intersection (n=6,438)	Pedestrian Refuge Islands	598.27 (2721.69)
		Pedestrian Leading Intervals	0.69 (2.94)
		Prohibit Right-turn on Red	0.11 (0.46)
Low risk	In between intersections/along corridors (n=4,248)	Barriers Installed on Top of Concrete Median	1.76 (6.55)
		Pedestrian-hybrid Beacons	1.60 (7.63)
		Road Diet	0.47 (3.52)
		Speed Limit Reductions - 10% decrease	0.15 (1.16)
	Unsignalized Intersection (n=282)	Pedestrian Refuge Islands	686.49 (1625.81)
		Advanced Stop/Yield Sign	42.79 (102.69)
	Signalized Intersection (n=938)	Pedestrian Refuge Islands	565.44 (2001.77)
		Pedestrian Leading Intervals	0.66 (3.15)
		Prohibit Right-turn on Red	0.10 (0.49)

In Table 13, the treatments are listed in descending order of BCR, which suggests the order among treatments does not differ by the predicted severity. However, the change in BCR by severity level implies some treatments might be preferred over the others in certain conditions. For instance, along the corridors, constructing barriers results in higher BCR than pedestrian hybrid beacons (4.54 versus 3.41 in high-risk regions). However, this difference diminishes to 1.76 versus 1.60 in low-risk regions. Although barrier construction still results in higher BCR, other factors not considered in this analysis result (e.g., aesthetics) may contribute to choosing pedestrian-hybrid beacons over barrier construction in low-risk regions.

The traffic delays derived from the treatments should be thoroughly considered since the treatments, which generate traffic delays, tend to have low BCRs. For instance, 10% speed limit reduction shows average BCR of 0.1 to 0.4, and prohibiting right-turn on red had the lowest BCR among all treatments considered in Table 13. Thus, these types of treatments (resulting in traffic delays) should be applied to select locations where fixing safety issues is more important than ensuring smooth flow of traffic.

DISCUSSION

Unfortunately, vehicle design largely neglects pedestrian safety. Both the United States National Highway Traffic Safety Administration (US NHTSA) and Insurance Institute for Highway Safety (IIHS) provide safety ratings for crashes with other vehicles and fixed objects only. The IIHS is now evaluating the quality of vehicles' autobraking technologies, but not their ability to protect pedestrians in the event of a collision (IIHS-HDLI, 2021).

The European Union (EU)'s European New Car Assessment Programme (Euro NCPA), on the other hand, includes pedestrian protection tests while evaluating the safety of vehicles sold in Europe. It measures how vehicles' bumpers and hoods protect pedestrians' lower legs at 40 km/h (24.85 mph) for both child and adult pedestrians (European Commission Mobility and Transport, 2021). As is the case in the US, the EU also assess the autobrake systems, but only when the vehicle performs well in the 40 km/h pedestrian impact test. Therefore, the car manufacturers not being required to test pedestrians' safety are contributing to the occurrence and severity of vehicle-pedestrian crashes in the US. This fact is already reflected in both the Euro NCAP's and IIHS' catalog of 'Best in Class' and 'Top Safety Picks' vehicle list, respectively. Euro NCAP has a much narrower list of vehicles with high ratings than the IIHS. American brands specifically scored poorly in pedestrian safety.

Therefore, even though the treatments suggested in this paper are important in terms of civil-engineering-oriented approaches, a more rigorous examination of vehicles' safety level, in terms of pedestrians' safety, should be included in the US' car ratings, to reverse the trend of vehicle-pedestrian crashes.

CONCLUSIONS

This paper investigated crash records from 2009 to 2019 in Texas. Pedestrians are less protected at an unsignalized intersection, resulting in higher crash records at these places compared to signalized intersections. The crash records by time-of-day and month-of-year imply that light conditions may be involved in triggering vehicle-pedestrian crashes, which can be supported by the finding that 30% to 40% of crashes occurred at dark conditions.

Eight treatments are suggested to reduce the crashes, which may cause delays to the vehicles, or may require installing additional facilities or modifications to existing infrastructure. The BCR results suggest that the benefits are higher than the required costs, with BCRs ranging from 1.67 to 1682. Each roadway, intersection, and segment have distinctive characteristics and reasons for their vehicle-pedestrian crashes, so an appropriate treatment designed to improve the conditions specified for each location should be attempted.

The classification model using SVM shows that crash records can be classified as high, medium, and low risk crashes after considering their crash attributes. A total of 10 distinctive attributes were selected to describe the conditions when the crash occurred and to extract featured details of the crashes. The developed classifier predicted the crash severity within reasonable error compared to the observed results. The same eight treatments mentioned above were applied to each of the crash records in the three risk levels and the average BCRs are derived. The results suggest some treatments can be prioritized over other treatments, but prioritization may differ by the crash's risk level. Also, some treatments may cause a significant amount of traffic delay, so the effects of each treatment should be considered before implementation.

Nonetheless, this paper focused on civil-engineering-oriented approaches to reduce vehicle-pedestrian crashes. Discussion on US vehicle safety regulations suggest a more rigorous examination of vehicles' safety level should be required. With the prioritization of treatments and safer vehicles, the increasing trend of vehicle-pedestrian crashes could be reversed, resulting in safer US road networks.

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