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A SYSTEM LEVEL ANALYSIS OF LEFT-TURNING VEHICLE-PEDESTRIAN CRASHES

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16. Abstract

Early research suggested protected left-turn signalization had clear safety benefits over permissive left-turn signalization. Yet, subsequent research on when and where to use protected left-turn signalization focused more on vehicle delay and throughput than on safety. Based on such studies, it would be easy to hypothesize that the use of protected left-turn signalization might be reserved more for intersections with high vehicle traffic than those with high pedestrian usage. Part 1 of this study seeks to test that hypothesis to see when and where traffic engineers implement protected left-turn signalization. Part 2 turns to questions around relative safety and addresses the challenges of assessing the possible safety implications of these implementation differences given the existing selective application. Part 3 takes a closer look at pedestrian severe intersection crashes and signalization practices in the state of Colorado to an understanding of the most impactful safety countermeasures to implement at intersections in terms of signalization and beyond.

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ABSTRACT

Early research suggested protected left-turn signalization had clear safety benefits over permissive left-turn signalization. Yet, subsequent research on when and where to use protected left-turn signalization focused more on vehicle delay and throughput than on safety. Based on such studies, it would be easy to hypothesize that the use of protected left-turn signalization might be reserved more for intersections with high vehicle traffic than those with high pedestrian usage. Part 1 of this study seeks to test that hypothesis to see when and where traffic engineers implement protected left-turn signalization. Part 2 turns to questions around relative safety and addresses the challenges of assessing the possible safety implications of these implementation differences given the existing selective application. Part 3 takes a closer look at pedestrian severe intersection crashes and signalization practices in the state of Colorado to an understanding of the most impactful safety countermeasures to implement at intersections in terms of signalization and beyond.

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PART 1: ASSESSING PROTECTED LEFT-TURN SIGNALIZATION PRACTICES

1. INTRODUCTION

Pedestrian fatalities account for approximately 17% of road fatalities (Stewart, 2023) but only 2.2% of trips (Census, 2021). A frightening number occur at intersections where pedestrians had the right-of-way. In San Francisco, for example, one-third of pedestrians had the right-of-way in crashes at crosswalks (Elinson, 2013). Drivers making left turns with permissive left-turn traffic signals strike many of these pedestrians. At such intersections with permissive left-turn signalization, traffic engineers give pedestrians a walk signal while simultaneously telling left-turning drivers to try and turn into that same crosswalk. In theory, left-turning drivers should scan the adjacent crosswalk, look for a gap in the oncoming traffic, check the crosswalk again, and then make their turn. In practice, drivers are often confronted with the prospect of looking for a gap in the oncoming traffic of a busy multilane road. Combine that with obscured vision from the A-pillar of many cars (Reed, 2008), headlights designed to shed light to the right of the driver instead of the left (Aranson, 2014), as well as the backpressure of waiting vehicles also trying to make the left-turn, and it is not surprising that some drivers do not properly check the crosswalk for pedestrians (Richard, Campbell, & Brown, 2006). In fact, research suggests that between 4% and 7% of left-turning drivers fail to fixate on the pedestrian in the conflicting crosswalk (Marnell, Tuss, Hurwitz, Paulsen, & Monsere, 2013). Left-turning drivers also strike and kill three to four times more pedestrians than right-turning ones (Lord, Smiley, & Haroun, 1998) (NYCDOT, 2016).

The early research comparing protected versus permissive left-turn signalization did not specifically consider pedestrian safety but did find better overall safety at intersections with protected signalization (ITE Florida Section, 1982; Agent, 1985; Agent, 1995). The subsequent strand of protected/permissive left-turn signalization research, however, glossed over safety and instead focused on how to increase vehicle capacity (Rathod, 2007*,* Yu, 2008). While more recent research begins to examine pedestrian safety more specifically, usually finding better pedestrian safety with protected signalization, the state-of-the-practice still seems focused on signalizataion that reduces vehicle delay (Qi, 2012; Chen, 2015; DePauw, 2015; Qi, 2017; Goughnour, 2021).

This begs the question as to whether current practice uses left-turn phasing to help protect vulnerable road users from left-turn conflicts and/or if they do so to reduce vehicle delay. Accordingly, our paper asks when and where traffic engineers use protected and permissive left-turn signalization in practice. This starts with an assessment of protected-only left-turn signalization usage by intersection and by left-turn movement. We then assess protected-only left-turn signalization by street type as well as a range of neighborhood characteristics. This includes considering differences in left-turn signalization based on street design, the relative level of walking and bicycling, and across the suburban-to-urban spectrum.

he next section delves deeper into the existing literature and its evolution over time. This is followed by an overview of our study, data collection efforts, and methods. We then detail the results and discuss the difficulties associated with evaluating potential safety implications arising from these implementation differences in light of current practice.

2. BACKGROUND & LITERATURE REVIEW

Protected versus permissive signalization research seemed to begin by examining the trade-off between safety and vehicle throughput. For example, one of the earliest left-turn phasing studies was conducted by a Florida subcommittee of ITE professionals in 1982 (ITE Florida Section, 1982*)*. The panel conducted before-and-after analyses of 28 intersections that had recently changed their signalization from permissive to protected-only phasing. The results showed a marked decrease in total crashes, dropping from 5.5 per year down to 0.5. Yet, despite the empirical results, the subcommittee sided with the findings of a driver-preference survey they also conducted and continued to discourage protected-only phasing as a general practice (except in cases of double left turns, poor sight distance, or other abnormalities related to intersection geometry).

Another early study by Agent in 1985 looked at 58 intersections in Kentucky that changed from protected-only to permissive left-turn phasing (Agent, 1985). Despite only selecting sites with good sight distances, speeds less than 45 mph, and two lanes of opposing traffic, Agent found that left-turn crashes nearly doubled with permissive phasing, going from 1.1 to 2.1 per approach per year. Yet, Agent still recommended against protected-only left-turn phasing (except at intersections with poor sight distances, speeds over 45 mph, or with more than three lanes of opposing traffic).

Subsequent academic research then left safety largely unexamined, instead focusing increasingly on the question of efficiency defined in terms of reducing vehicle delay (Agent, 1995; Rathod, 2007; Yu). In one of the few papers that did mention safety, Upchurch studied six intersections and found that the average crash rate (per million entering vehicles) was markedly lower for protected-only phasing (0.94) than for permissive (3.68) or protected/permissive (2.24) (Upchurch, 1986). The results also suggested that at lower volumes, permissive phasing could save two to three seconds of delay per left-turning vehicle. At bigger intersections with higher volumes, protected or protected/permitted left-turn phasing could save four to five seconds. The signalization recommendations, again, were optimized for reducing vehicle delay rather than increasing safety (Upchurch, 1986). Such findings led to a generation of researchers trying to find the exact volumes or conditions at which to switch from permissive to protected (or protected/permissive) in order to minimize vehicle delay (Agent, 1995; Martin, 1998; Rathod, 2007; Yu, 2007; Yu, 2008).

The general progression of the protected/permitted left-turn phasing research suggests that protected signalization might be reserved for larger intersections with higher traffic volumes and fewer pedestrians. However, we also were unable to find much, if any, research asking when and where traffic engineers use protected versus permissive left-turn signalization. Instead, there is a growing strand of more recent research refocusing the left-turn phasing question onto pedestrians (Chen, 2015; Depauw, 2015; Qi, 2017; Goughnour, 2021). The initial pedestrian-focused studies continued the tradition of minimizing vehicle delay but did so while asking how to best introduce a pedestrian signal phase (Urbanik, 2000; Tian, 2001*)*. In terms of safety, Urbanik's simulation paper found far fewer pedestrian-vehicle conflicts with protected or protected/permitted phasing but continued to recommend it in most cases (Urbanik, 2000). Tian (2000) tried to find cases where exclusive pedestrian phasing may actually help reduce vehicle delay but ended up determining that the vehicle capacity of permissive phasing outweighed the increased risk of pedestrian conflicts except in rare situations "with high pedestrian volumes, wide crossings, and relatively low traffic demand" (Tian, 2000). However, without answering larger questions around how often protected only phasing is used and the context of its application, this strand of pedestrian focused research still leaves a gap in our general understanding of how pedestrians are impacted.

Eventually, the research starts to question these priorities, at least to some extent. For example, Srinivasan et al. studied Winston-Salem, North Carolina, and found that protected left-turn phasing nearly eliminated left-turn crashes (Srinivasan et al., 2008). This study, however, did find some crash migration toward other less severe crash types. In terms of pedestrian safety, Qi and Guoguo used micro-simulation to model pedestrian crashes and found permissive left-turn phasing to be among the significant pedestrian crash risk factors (Qi & Guogo, 2017). Chen et al. (2015) focused on empirical safety outcomes of 68 New York City intersections that changed to protected-only signalization. Though overtaking crashes increased, they found significant reductions in both pedestrian crashes and left-turn crashes. The authors still hesitated to recommend protected-only phasing as the default approach other than in very high pedestrian volume situations; however, this recommendation runs counter to existing guidance that relies more on vehicle volumes, number of lanes, posted speeds, and sight distance to determine when protected-only phasing is appropriate.

More recently on pedestrian safety, Goughnour et al. (2021) conducted a comprehensive assessment of signalization changes at 215 intersections across four cities. Unfortunately, only 12 of the 215 intersections changed to or away from protected-only, with eight of those 12 all in New York City. This left them without statistically significant results for vehicle–pedestrian crashes with respect to protected-only signalization. While the results suggest the safety benefits increase with more pedestrians, they did not seem to have enough examples of protected-only signals to say so conclusively.

While several papers suggest safety benefits with protected-only phasing, particularly in contexts with pedestrians, the overarching research seems more focused on using protected-only signal timing to optimize vehicle throughput. Whatever the rationale behind the use of protected-only phasing, the existing research leaves questions about the landscape of current implementation of protected-only phasing relatively unexplored. At most, the existing research touches briefly on the prevalence of use but relies on either small samples of signals or through surveys of jurisdictions. The need remains for a more comprehensive examination of current signalization practices before questions about pedestrian safety can be adequately addressed. To address this gap in the existing research, we first want to understand when and where traffic engineers implement protected-only signalization at the intersection level. We then seek to understand the context of usage in terms of street type, neighborhood characteristics, and the relative level of walking and bicycling. While better understanding the safety implications of these choices is also important, a lack of protected-only signals in more urban areas with more pedestrians could make it difficult to evaluate the safety impacts. Accordingly, our paper will also assess safety but with an eye on the hurdles we face in answering what seem like basic safety questions.

3. RESEARCH STRATEGY, METHODOLOGY, & DATA

3.1 Study Overview

By taking a comprehensive look at all left-turn signal phasing across multiple cities, we attempt to understand the current landscape of left-turn signal phasing application. We also seek to understand what types of streets and what type of places implement protected-only left-turn phasing. We do this through a phased analysis in which we first look at the overall prevalence of left-turn signal phasing application. We then look at left-turn signal phasing at the street and census block group level to understand how application relates to street characteristics, relative urbanity, as well as the relative level of walking and bicycling.

3.2 Data Collection

3.2.1 Site Selection

We contacted 32 midsized U.S. cities, ranging in population from 300,000 to 700,000, to request general left-turn signal phasing data. Somewhat surprisingly, few such cities compile comprehensive data about their signalization practices. Most responded that a detailed analysis of each signal timing plan would be needed in order to obtain the information we were seeking. However, several cities were able and willing to provide some baseline information regarding their left-turn signal phasing that we could then supplement.

Accordingly, our sites were largely selected based on the level of data available. These include St. Paul, MN, Aurora, CO, Cincinnati, OH, and Raleigh, NC. Given that our research relies heavily on available data from the few cities that were able and willing to provide signal data, we must acknowledge the potential for self-selection bias, wherein the cities that collect and track these data may not be representative of all cities.

3.2.2 Signal Data

As mentioned, obtaining consistent data across various jurisdictions presented some challenges as few cities could provide a complete set of all the data we were seeking. As a result, we supplemented our data to fill gaps and standardize the data across the selected cities. While this process may introduce error, we strived to limit potential issues as much as possible. Given variations in signalization practices across cities, we standardized the data by sorting them into signalization categories. More specifically, we categorized signal phasing into the following three categories in order to standardize it across all four cities:

- Permissive
    - Signals that allow vehicles to turn left as gaps in traffic appear without green or red arrows were placed in the permissive category (Rodegerdts et al., 2004)
- Protected/Permissive
    - Protected/permissive phasing consisted of any phasing that mixed both protected left turns with permissive phasing (Rodegerdts et al., 2004). This typically meant a lead or lag protected left-turn phase followed or preceded by a permissive phase, but it also involved other timing plans with mixed modes. For example, we classified cases where left-turn phasing changed by time of day as protected/permissive phasing, even though the protected-only phase may be implemented periodically.

- Protected-only (PO)
    - Protected-only signals included left-turn phasing that temporally eliminated conflicts between left-turn vehicles and oncoming traffic and pedestrians and bicyclists (Rodegerdts et al., 2004).

We filled any remaining gaps based on the information that each city provided about their general practices related to signalization with respect to signal head type. We then used Google Earth and Google Street View to identify the signal head type in use and cross-referenced that with the information they provided related to typical signalization. As such, the data on signal phasing was a snapshot in time and may not perfectly correspond with the complete set of crash data spanning five years. We then aggregated at the street and census block group levels.

3.2.3 Left-turn Signalization by Street Type

To understand how street characteristics relate to signal phasing implementation, we collected street centerline data and volume data from each jurisdiction and supplemented that with Global Urban Street Network GeoPackage from the Harvard Dataverse for node and edge data (Boeing, 2020). Data collected included speeds, number of lanes, functional class, and volumes. While functional class was fairly easy to obtain for all roads within each city, lack of standardization in application of the classes makes drawing any meaningful conclusions difficult across so many cities. As such, we instead relied on more quantitative values such as traffic volumes, posted speeds, and the number of lanes.

3.2.4 Left-turn Signalization by Neighborhood Characteristics

Because urbanism has been shown to increase the likelihood of walking and biking behaviors (Ewing & Cervero, 2010), we also sought out data that could speak to how urban or suburban a neighborhood might be. Research has established a close tie between the degree of urbanism and intersection density (Boeing, 2018; Ewing & Cervero, 2010). As such, we included intersection density as a proxy to account for variation in the level of urbanism. In addition to intersection density, we also included population density as a metric that could also serve as a proxy for urbanism (Boeing, 2018). Intersection density and population density were obtained by census block group from the Center for Neighborhood Technology, which aggregates intersection density per square mile for each census block group.

3.2.5 Risk and Exposure

While our study's focus was on the current practice of left-turn signal phasing, we also sought to understand what factors practitioners consider, such as the prevalence of pedestrians and bicyclists, when deciding upon signalization. In order to estimate pedestrian and bicyclist counts on an apples-to-apples basis across our cities, we first considered big data options such as Streetlight. However, the research suggests that error rates and access costs tend to be high (Kothuri, et al., 2022). Therefore, we chose to use American Community Survey Mode to Work at the census block group level as proxies for pedestrian and bicyclist volumes (Beck, Dellinger, & O'Neil, 2007*32*; FHWA, 2015).

3.3 Methodology

The intent of the methods described below was to take the signalization data described above and answer the following questions:

1. How often is protected-only left-turn phasing used?
2. Where is protected-only left-turn signalization used with regard to street and neighborhood contextual characteristics?

To accomplish this, we first used GIS to aggregate the signalization data at the intersection, street, and census block group levels.

At the intersection level, for instance, we sorted intersections into groups based on what percentage of the signals within the intersection were protected-only, protected/permitted, and permissive-only to better understand how often each is used overall, and to better inform our sorting of the data on signalization practices at the street and census block group level.

For the street-level analysis, we sorted intersections into groups based on whether they had any protected-only left-turn phasing or not. We then used GIS to aggregate street characteristics, including posted speed, average annual daily traffic (AADT), and the number of lanes to compare signalization levels of each grouping. Finally, we tested for statistical significance of these groups using a t-test.

For the area-level analysis, we used GIS to aggregate signal phasing data, street data, pedestrian and bicyclist commute mode share, intersection density, and residential density at the census block group level. For posted speed aggregated by census block group, we calculated the average posted speed of all streets within each census block group. Similarly, for AADT, we took the average AADT on all streets where AADT was recorded in the census block group.

We then sorted the census block groups into categories of protection level. Determining the thresholds to define each group proved challenging due to the uneven distribution of the data. Because over half of the census block groups in our sample had zero protected-only signals, the census block groups could not be split into even quartiles. Therefore, once the zero-protection group was excluded, the remaining three groups were sorted into three relatively similarly sized groups. Accordingly, we compare zero protection with low protection (defined as greater than zero and up to 16.7% or one out of every six signals is protected-only), medium level of protection (defined as over 16.7% up to 33.3% of signals being protected-only), and high levels of protection were defined as census block groups with over 33.3% of their left-turn signal movements being protected-only. We then applied single factor analysis of variance (ANOVA) to determine the level of statistical significance between the four groups for each variable tested.

In the last phase of analysis, we sought to break the groups into quartiles based on their relative level of urbanity. To capture variation along the urban-to-suburban spectrum, census block groups were grouped into quartiles based on the number of intersections per square mile. High intersection density (over 244 intersections per square mile), high medium intersection density (Mid High ID= intersections of 179 to 244 per square mile), low medium intersection density (Mid-Low ID= intersections 108 to 179 intersections per square mile), and low intersection density (LID= interactions under 108 intersections per square mile). We then examined left-turn signalization practices, pedestrian and bicyclist commute mode share, and residential density in each category. To determine the level of statistical significance, we applied single factor ANOVA to each variable.

4. RESULTS

4.1 How Often are Protected-only Left-turn Signals Used?

Our results show that despite the body of research suggesting safety benefits associated with protected-only left-turn phasing, traffic engineers infrequently use protected-only phasing in the field. We first consider usage by intersection and then do so by left-turn movement.

4.1.1 Left-turn Signalization Prevalence by Intersection

Our study of nearly 70,000 intersections across four cities included 2,134 signalized intersections. Table 4.1 shows that permissive left-turn phasing remains the dominant form of controlling intersection signalization. Traffic engineers employed full-protected left-turn signals in less than 6% of those signalized intersections. Protected/permitted signal phasing was employed in 5% of signalized intersections. This includes nearly 50% of all signalized intersections having 100% permissive left-turn movements and 83% having at least one phase of permissive left-turn phasing. While 81% of signalized intersections have at least one phase that is permissive, only a small fraction (21%) of signalized intersections have at least one protected-only.

Table 4.1 Intersection Left-turn Signal Phasing Mix

Intersection Phasing Composition	Total Number	Percent
Total Intersections	69,559	
Total Signalized Intersections	2,134	3.07%
Total Signalized Intersections that Include Left-Turn Movements	2,110	3.03%
Total Signalized Intersections that have any Permissive	1,708	80.95%
Total Signalized Intersections that are 25% Permissive	75	3.55%
Total Signalized Intersections that are 50% Permissive	426	20.19%
Total Signalized Intersections that are 75% Permissive	204	9.67%
Total Signalized Intersections that are 100% Permissive	1,053	49.91%
Total intersections that have any Protected/Permitted	767	36.35%
Total intersections that have 25% Protected/Permitted	224	10.62%
Total intersections that have 50% Protected/Permitted	393	18.63%
Total Intersections that have 75% Protected/Permitted	44	2.09%
Total Intersections that are 100% Protected/Permitted	106	5.02%
Total Intersections that have any Protected-Only	440	20.85%
Total intersections that have 25% Protection (Protected-Only)	55	2.61%
Total intersections that have 50% Protection (Protected-Only)	234	11.09%
Total intersections that have 75% Protection (Protected-Only)	25	1.18%
Total intersections that have 100% Protected-Only	126	5.97%

4.1.2 Left-turn Signalization Prevalence by Left-Turn Movement

Because of the various combinations of left-turn signal phasing that exist, even within a single intersection, we aggregated the data by left-turn movement to further clarify the picture. The results again suggest that protected-only left-turn phasing is rarely used for controlling left-turn movements, and that the vast majority of left-turn movements are controlled through permissive left-turn phasing. More specifically, Table 4.2 shows that approximately 20% of left turns have a mix of phasing types with protected/permitted phasing. This means that 86.6% of signalized left-turn movements include permissive signalization while 13.4% of signalized left-turn movements are protected via signalization.

Table 4.2 Left-turn Signal Phasing by Left-turn Movement

	Total left turn movements	Total signalized left-turn movements
Total left-turn signalized movements	6,948	
Total left-turn movements with permissive phasing	4,654	66.98%
Total signalized left turns controlled with protected/permitted left-turn phasing	1,365	19.65%
Total PO controlled left-turn movements	929	13.37%

With such sparse use, the question of when and where protected-only phasing is used naturally arises. For instance, the existing safety research identifies the importance of uniform phasing applications (Yu et al., 2008). However, the rare use of protected-only phasing also suggests that it is unlikely to be applied uniformly at a corridor or regional level. Still, further analysis at the street and census block group level is needed to understand how uniformly it may be applied across a corridor or region. Accordingly, in the following sections, we seek to answer the question of where protected-only phasing is used by looking at protected-only phasing at the street level and at the census block group levels.

4.2 Where are Protected-only Left-Turn Signals Used?

The infrequent use of protected-only phasing in Table 4.1 and Table 4.2 above raises the question of where protected-only phasing is used, and if it is employed on different types of streets and contexts than where permissive phasing is used. To answer this question, we first look at what types of street characteristics are associated with protected-only phasing signalization. We then look at what types of places are associated with protected-only phasing by looking at signalization practices at the census block group level. By examining signalization practices at the census block group level, we can also introduce variables related to active transportation exposure via pedestrian and bicyclist commuting mode share.

4.2.1 Left-turn Signalization by Street Type

The street-level analysis in Table 4.3 shows that protected-only phasing is significantly more likely to be present on high-capacity streets with four or more lanes than intersections without protected-only phasing. Additionally, intersections with protected-only phasing are much more likely to be on roads having a posted speed limit of 35 mph or higher, as the share of intersections with protected-only phasing increases along with the posted speed. Although insignificant, our results also show that intersections with protected-only signal phasing have 20% more traffic volume on average than intersections that lack protected-only phasing.

Table 4.3 Streets Characteristics of Protected-only Intersections

	Non-PO Intersection	PO Intersection (Having at least one PO signal)	Percent Difference	P value
Number of intersections	1,670	440		
Intersecting with street 35 mph or over	62%	89%	36%	0.05
Intersecting with street 45 mph or over	23%	56%	82%	0.04
Intersecting with street of 4 or more lanes	72%	99%	32%	0.05
Average AADT of intersecting street	16,173	19,742	20%	0.10

4.2.2 Left-turn Signalization by Neighborhood Characteristics

The street-level results, which show that protected-only phasing is strongly associated with higher-capacity, higher-speed roadways, raise the question of what types of neighborhoods implement protected-only phasing more consistently. To answer this question, Table 4.4 presents the census block group level results, where metrics indicative of the level of urbanity (intersection density, residential density) have been aggregated to understand where the protected-only left-turn application falls on the urban-to-suburban spectrum.

Table 4.4 Protection Level at the Census Block Group Level

	n	% Arterial	Average AADT	Avg. Posted Speed (mph)	Density (Pop/acre)	Intersection Density (intersections per sq. mi.)	% Pedestrian Commuters	% Bicyclist Commuters
No Protected Signals (0%)	653	19%**	6787**	25.1**	10.3**	202.2**	3%**	1%
Low Level of Protected Signals (>0% and ≤16.7%)	161	29%**	10841**	26.2**	8.7**	256.2**	5%**	0.5%
Medium Level of Protected Signals (>16.7% and ≤33%)	146	27%**	12340**	29.6**	7.2**	156.3**	2%**	0.4%
High Level of Protected Signals (>33%)	130	28%**	16847**	30.1**	7.1**	133**	2%**	1%

*denotes a p value of .005 or less
**denotes a p value of .001 or less

Despite attempts to obtain a broad set of evenly distributed data, our results skew heavily to census block groups having no protected-only signal phasing at all. In fact, over half of all census block groups had zero protected-only signals. While the lack of protected-only phasing in the bulk of the census block groups reiterates the sparsity of its use, it also presents a difficulty in drawing comparisons between such unevenly distributed groups. Nevertheless, our results were still found to be statistically significant and suggest that protected-only phasing tends to be applied in more suburban census block groups with lower intersection density, lower share of pedestrian commuters, and lower population density. Given the established association between intersection density and relative level of urbanity (Boeing, 2018), we next sorted census block groups by level of urbanity via intersection density to understand how levels of protection along with pedestrian and bicyclist exposure varied across contexts. This analysis also allows for analysis through four equal quartiles. Consistent with our Table 4.4 findings, Table 4.5 shows that as intersection density increases, so does the residential density and pedestrian and bicyclist commute share. As shown in Table 4.5, the share of permissive left-turn phasing also increases with higher intersection density as protected-only left-turn phasing decreases. In other words, these results confirm that protected-only signal phasing is rarely used where vulnerable road users are more likely to be exposed to crash risk.

*denotes a p value of .005 or less
**denotes a p value of .001 or less

Table 4.5 Protection Level on the Urban to Suburban Scale

	n	% Protected Signals	% P/P Signals	% Permissive Signals	% Pedestrian Commuter	% Bicyclist Commuter	Density (pop/acre)
Low Intersection Density (≤108 per sq. mi.)	276	19.7%**	22.5%**	45.1%**	.9%**	.21%**	3.9**
Low-Medium Intersection Density (>108 per sq. mi. and ≤179 per sq. mi.)	272	12.1%**	20.3%**	59.5%**	1.1%**	.22%**	7.6**
Medium-High Intersection Density (>179 and ≤244 per sq. mi.)	270	7.9%**	18.4%**	58.2%**	1.7%**	.5%**	11.4**
High Intersection Density (>244 per sq. mi.)	272	5.8%**	14.4%**	63.9%**	3.3%**	.6%**	14**

5. CONCLUSIONS

We found that protected-only left-turn signalization is used infrequently in practice. Only 20% of signalized intersections include protected-only left-turn phasing. When protected signalization is used, it typically appears as an isolated treatment in a sea of permissive-only phasing with more that 80% of signalized left-turn movements remaining permissive.

As for where protected-only left-turn phasing signalization is used, our street-level analysis showed higher prevalence with higher speeds, higher capacity, and higher vehicle volumes. Of protected-only signals, 86% intersect with a street having a speed limit of 35 mph or higher, and nearly 100% intersect with a street of four or more lanes. Regardless of signalization, these factors tend to be associated with a higher risk for severe and fatal crashes. These are also streets that are less inviting to vulnerable road users with our results showing lower pedestrian mode share and lower residential density in neighborhoods with the highest levels of protected-only left-turn signalization. Residential density was 42% higher in census block groups with no protected-only signal phasing than in census block groups with the highest percentage of protected-only signal phasing; pedestrian mode share was 50% higher in census block groups with no protected-left turn signals than in census block groups with the highest percentage of protected-left turn signals.

Given the early research, we expected to see a wider application of protected-only left-turn phasing. Yet, our results show just the opposite. Unfortunately, sparse protected signalization makes it difficult to further the safety research. In other words, our results suggest that traffic engineers first need to use protected-only left-turn phasing at a broader and/or more uniform scale before we can adequately study the safety impacts more comprehensively. Fortunately, a growing focus on safe systems and Vision Zero frameworks presents an opportunity for traffic engineers to rethink priorities, particularly where vulnerable road users are most likely to be, with their approach to signalization. As such, future research should focus on how shifts in the application of left-turn signal phasing impacts safety of vulnerable road users when these practices take hold on a broader scale.

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PART 2: BIKE & PEDESTRIAN SAFETY VIA LEFT-TURN SIGNALIZATION PRACTICE

7. INTRODUCTION

Permissive left-turn signalization is standard practice in most American cities. Early research showed that this practice came with a clear trade-off in safety. Yet, subsequent research took the use of permissive left-turn signalization as a given and focused more on vehicle throughput. While Part 1 of this report focused on the resulting landscape of signalization practices, Part 2 seeks to examine how the corresponding transportation system impacts vulnerable road users given the known conflict with left-turning vehicles that permissive left-turn phasing entails. Because the resulting transportation system may impact various levels of decisions beyond intersections, we examined this question using an area study approach at the census block group level. Accordingly, we consider vulnerable road user safety with respect to left-turn signal phasing using five years of crash data across four cities.

Of the 17% of road fatalities that were pedestrian crashes, a frightening number occurred at intersections and crosswalks where pedestrians had the right of way (Stewart, April 2023). In San Francisco, for example, one-third of pedestrian crashes occurred at crosswalks where pedestrians had the right-of-way (Elinson, 2013). Similarly, driver yield rates were observed to average only 16% in field studies of pedestrians attempting to cross at 20 uncontrolled marked crosswalks where they had the right-of-way (Schneider, 2018). One particularly dangerous crash type for pedestrians are left-turn crashes at signalized intersections. Left-turn pedestrian-vehicle crashes outnumber right-turn pedestrian-vehicle crashes by a factor of 3 to 1 (Lord, 1998). They also tend to result in more severe injuries than most other crash types (Wang, 2008).

Despite the known dangers, left-turn vehicle-pedestrian safety receives comparatively little research or consideration (Qi, 2012; Amiridis, 2017). Early studies showed that protected-only left-turn signal phasing resulted in lower crash risk (ITE Florida Section, 1982; Agent, 1985; Agent, 1995). Subsequent research glossed over such results and instead focused on when and where to use protected-only phasing as a tool to increase vehicle capacity (Rathod, 2007). This research aims to reopen the question of whether strategies that reduce conflicts between vulnerable road users and left-turning vehicles lead to safer outcomes.

Unfortunately, it is difficult to fairly assess safety differences in a transportation system where permissive left-turn phasing has become the default. On top of the sparse use, limiting analysis to an intersection level also fails to account for behaviors that may be a rational response to high-risk intersections. For instance, if a pedestrian decides to cross mid-block because of perceived safety issues at an intersection with a permissive-left turn phase (where they are in direct conflict with left-turning vehicles) and gets hit, that crash would not be attributed to that intersection. We attempt to control for this phenomenon by conducting an area-level study of current practices in left-turn signal phasing across 1,090 census block groups in four U.S. cities. We then assess these differences with respect to fatal or severe injury crashes for all road users as well as those involving pedestrians or bicyclists.

The next section delves deeper into the existing literature and how it evolved. This is followed by an overview of our study, including our data collection efforts. We then detail the results and discuss them in light of current practice.

8. BACKGROUND & LITERATURE REVIEW

Within the body of research on left-turn signal phasing, startlingly few studies focus on questions of pedestrian and bicycle safety, consistently relegating safety considerations to concerns over vehicle delay. The best information we have about the relative safety of left-turn signal phasing comes from the earliest studies in the 1980s where before-and-after studies were conducted at intersections to compare crash rates among protected-only, protected/permissive, and permissive-only phasing (ITE Florida Section, 1985; Martin, 1986). Such research consistently showed protected-only signal phasing to be markedly safer in terms of the lowest crash rates (Agent, 1985; ITE Florida Section, 1982; Martin, 1998; Rathod, 2007; Tian, 2001; Upchurch, 1986; Urbanik, 2000; Yu, 2008; Yu, 2007). Regardless of the clear benefits in safety that emerged, each research team proceeded to recommend implementation of protected-only phasing as a spot treatment for higher risk conditions, such as poor sight distance, existing crash history, high speeds, high vehicle volumes, or more than three opposing lanes of traffic, but recommending protected/permissive or permissive phasing as the default mode of controlling left-turn movements (Martin, 1998; Agent, 1985).

Questions about pedestrian safety do not appear in the research until years after the earliest studies. In 2000, researchers began to introduce questions regarding pedestrian signal phasing, but the focus continues from the perspective of how to minimize vehicle delay while integrating the pedestrian phase (Urbanik, 2000; Tian, 2001). A 2000 study recommended protected/permitted phasing despite clear evidence of fewer pedestrian conflicts with both standard and split protected-only phasing (Urbanik, 2000). A 2001 follow-up study proposed a model for determining when the use of protected-only pedestrian phasing under split-phasing operations can be more efficient compared with the standard protected left-turn display phasing scheme. “The use of an exclusive pedestrian-phasing scheme is favored with high pedestrian volumes, wide crossings, and relatively low traffic demand.” (Tian, 2001) While the model took pedestrian volumes into account, the proposed model’s recommendations revolve around questions of vehicle efficiency rather than on pedestrian safety.

Subsequent research left recommendations for permissive and protected/permissive left-turn phasing as the default mode largely unexamined, focusing increasingly on the question of optimizing for efficiency defined in terms of vehicle delay. This segment of the research focused either on how to optimize timing plans (Rathod, 2007; Yu, 2008; Agent, 1995) or how roadway and geometric design could be altered to minimize delay (Yu, 2007; Martin, 1998). While questions of safety were still mentioned to some extent, the focus centers around minimizing vehicle delay without increasing crash rates beyond what were considered acceptable thresholds. In 2007, for example, one researcher developed a model for predicting the optimal time to switch from protected to permitted in permitted/protected timing plans (Rathod, 2007). These researchers consistently find that protected-permissive phasing is the best option in terms of efficiency due to its adaptability to various fluctuations in vehicle volumes.

A 2007 study stands out in looking at safety at a system level. While the researchers focused most of their attention on questions around optimizing for vehicle delay, they took the research a step further by looking at the system level safety impacts and finding that overall uniformity in signal phasing practices, regardless of types, is associated with lower crash risk (Yu, 2007). Another study also focused their attention on safety, but found mixed results associated with protected-only signal phasing, with the decrease in left-turn crashes offset by an increase in other, commonly less severe, crash types (Srinivasan, 2008). Because the focus was on total crashes, this research missed the opportunity to examine whether there was an overall decrease in serious injury and fatality crashes.

Where the early research centered decisions about phasing choice and integration of pedestrian phases on vehicle efficiency, more recent research in this area refocuses the question of phasing choice on pedestrian safety (Yi Qi, 2017; Chen, 2015; DePauw, 2015; Goughnour, 2021). Research in this area largely shows marked improvement in left-turn crashes and pedestrian crashes, but findings in total crashes are mixed (Chen, 2015). Only one of the studies in this group failed to find significant benefits associated with protected phasing, but further examination revealed that the research grouped protected/permitted and protected-only phasing together, making it difficult to draw any conclusions about the relative safety of protected-only left-turn phasing (Goughnour, 2021).

Perhaps the most direct study on the question of pedestrian safety was conducted in the highly urban context of New York City, looking at bicycle and pedestrian safety at intersections recently changed from permissive to protected-only and protected/permissive left-turn phasing. While the results showed significant reductions in pedestrian, bicycle, and left-turn crashes, the study authors glossed over such findings that focused on the increase in overtaking crashes. Because of the mixed results, the authors cautioned against the implementation of protected-only phasing as a standard approach and instead recommended its use in contexts with high pedestrian volumes. This recommendation runs contrary to the findings in Part 1 of this report that suggest vehicle volumes, number of lanes, posted speeds, sight distance, and existing crash history to be the determining factors for left-turn phasing type. While this strand of the research does an excellent job of setting up the question of how left-turn phasing practices impact pedestrian and bicycle safety, the discussion and recommendations miss the opportunity to answer questions about how to reduce the most severe and fatal crash types by focusing on total crashes.

In summary, the safety benefits of protected-only phasing are well established at the intersection level, but the majority of the research plays down this finding in an effort to focus on the granular details of timing and sequencing to reduce vehicle delay. The question of pedestrian and bicyclist impacts did not join the conversation until the early 2000s, and much of this research area still focuses on questions of efficiency over safety. Only in the last 10 years have questions about pedestrian safety emerged as a central question, but the existing research in this area fails to examine safety beyond the intersection level (Chen, 2015; Goughnour, 2021). Few of the studies isolate protected-only phasing (Goughnour, 2021), and those that do consider only a handful of intersections with protected-only phasing, making it difficult to draw any statistically significant conclusions (Chen, 2015). As a result, conclusions and recommendations often group protected-only and protected-permissive together, and the marked improvements in safety associated with protected-only phasing get diluted (Chen, 2015). To understand if this association applies in broader contexts and if safety benefits can be detected beyond the intersection level, we study the impact at the census block group level in four mid-sized U.S. cities. With an area level approach, we seek to understand 1) where current practice applies protected-only phasing, and 2) what the overall safety impacts are. Our focus here is on serious injuries and fatalities among bicycle and pedestrian crash types, where many of the existing studies focused on total bicycle and pedestrian crashes.

9. RESEARCH STRATEGY, METHODOLOGY, & DATA

9.1 Study Overview

While the existing body of research establishes the relative safety benefits of protected-only left-turn signal phasing at the intersection level, such methods are insufficient to answer questions about global safety impacts and how context might influence safety. Given the more recent findings showing that benefits of protected-only phasing may be greatest in contexts with high pedestrian volumes, a comprehensive examination of current practice is needed to understand if signal warrants, relying largely on vehicle volumes and other vehicle related metrics, leave any gaps that could put bike riders and pedestrians at unnecessary risk.

Because current guidance recommends protected-only left-turn phasing in known high-risk areas, it is anticipated that census block groups with higher concentrations of protected-only phasing may actually have higher crash rates than permissive dominant census block groups regardless of the signalization practices. Therefore, the study is designed to first demonstrate the broader impact of current signal phasing guidance on vulnerable road user safety, and then to control for any confounding variables that may be also influencing crash rates to determine if there are indeed broader safety benefits of protected-only signal phasing.

We first look at the total SI/fatal (serious injury/fatal) crashes and total SI/fatal bicycle and pedestrian crashes in each census block group to understand if census block groups with a high proportion of protected-only left-turn signal phasing are associated with lower crash rates. Next, we look at this same question but sorted along the urban to suburban spectrum. Last, we look at the highest crash quartile of census block groups to examine if protection level influences safety in neighborhoods with high levels of crash risk. While examining differences within the most extreme quartile may introduce risk of error related to outliers, because crash history is an additional factor that typically triggers implementation of protected-left turns, viewing crashes through this lens further controls for some of the confounding variables influencing crash rates.

9.2 Data Collection

9.2.1 Site Selection

We contacted mid-sized U.S. cities between 200,000 and 700,000 in population to request data on general left-turn signal phasing. Somewhat surprisingly, few cities compile such comprehensive data about their signals. Most cities responded that a detailed analysis of each timing plan would be needed in order to obtain the information we were seeking. However, there were four cities able and willing to provide information regarding their left-turn signal phasing: St Paul, MN; Aurora, CO; Cincinnati, OH; and Raleigh, NC.

9.2.2 Signal Data

We collected signal data from each jurisdiction and the state DOT where appropriate. Obtaining consistent data across various jurisdictions presented a number of challenges, as variation exists between signal phasing practices in each jurisdiction. As such, we then categorized signal phasing into Permissive, Protected/Permissive, and Protected-only categories to standardize it across all four cities. Signals that allow vehicles to turn left as gaps in traffic appear without green or red arrows were placed in the permissive category (Rodegerdts et al., 2004). Protected/permissive phasing consisted of any phasing that mixed both protected left turns with permissive phasing. This typically meant a lead or lag protected left-turn phase followed or preceded by a permissive phase, but it also involved other timing plans that mixed modes of controlling left turns by time of day. For example, we classified cases where left-turn phasing changed by time of day as protected/permissive phasing even though the protected-only phase may be implemented periodically. Protected-only signals included left-turn phasing that eliminated conflicts between left-turning vehicles and oncoming traffic and bike riders and pedestrians (Rodegerdts et al., 2004).

Few cities were able to provide a comprehensive list of data for all signals, so we filled gaps using Google Earth and Google Street View to understand general left-turn signal phasing where gaps existed. As such, the signal phasing data were merely a snapshot in time and may not perfectly correspond with the complete set of crash data spanning five years.

Another issue that arose was finding a large enough sample of protected-only left-turn phasing to draw broader conclusions about relative safety. Because protected-only left-turn phasing is typically only applied as a spot treatment to mitigate other high-risk factors, there are very few scenarios where protected-only left-turn phasing is used as a standard practice. In an attempt to minimize issues surrounding a small sample size that may be easily skewed by other high-risk factors associated with implementation, signal phasing data were collected for all signalized intersections in four cities.

9.2.3 Crash Data

We collected geospatial crash data from each city for 2015–2019 as these years of data were the most recent available for all four cities. Crash types analyzed included bike and pedestrian severe injury and fatality crashes, and total severe injury and fatality crashes. To standardize the data across jurisdictions where definitions differed, we consulted the data dictionaries in each city to group crash types by attributes that were as similar as possible. Not all jurisdictions define severe/serious injury crashes in the same way. Many use an injury level scale while others have a separate serious injury crash category. In cases where a scale was used, we only counted crashes in the highest injury category that did not include fatalities. While we intended to include left-turn crashes as a separate category, we did not include this crash type in the analysis because of the difficulty in finding consistent ways to define these crash types.

9.2.4 Built Environment Context

Research has established a close tie between the built environment context and intersection density (Ewing, 2010). As such, we decided to include intersection density as a proxy to account for variation in the built environment context. Data for intersection density were obtained by census block group from the Center for Neighborhood Technology, which aggregates intersection density per square mile for each census block group. Intersection density was used to represent different context zones to control for various factors such as number of conflict points, walkability, speeds, and arterial lane miles that may also be impacting crashes in the various contexts.

9.2.5 Exposure

To get a better understanding of how comparatively risky each census block group was in light of the raw crash numbers, we obtained population data and data on bike and pedestrian commuters for each census block group from the 2019 American Community Survey Mode to Work dataset.

Because we were analyzing crashes relating to vulnerable road users, finding exposure data was difficult in the absence of robust and accurate estimates of annual average pedestrians or bicyclist counts. While there are a few data sources that do have pedestrian and bicyclist counts such as Streetlight, error rates tend to be high and costs to access such sources can be high (Khatouri, 2022). Therefore, we chose to normalize the data using two methods. First, we looked at crash data in relation to the census block group population, which is a well-established method of capturing relative exposure for area level studies accepted by both NHTSA and the National Safety Council. Commuter mode share is also a well-established method of estimating exposure. Therefore, we chose to use American Community Survey Mode to Work at the census block group level as proxies for pedestrian and bicyclist volumes (Beck, Dellinger, & O'Neil, 2007; FHWA, 2015).

9.2.6 Street Data

To understand how street characteristics relate to signal phasing implementation, we collected street centerline data and volume data from each jurisdiction and supplemented those with Global Urban Street Network GeoPackage from the Harvard Dataverse for node and edge data (Boeing, 2020). Data collected included speeds, number of lanes, functional class, and volumes. While functional class was fairly easy to obtain for all roads within each city, lack of standardization in application of the classes makes drawing any meaningful conclusions difficult across so many cities. We instead relied on more quantitative values such as traffic volumes, posted speeds, and the number of lanes.

9.3 Methodology

The intent of the methods described below was to take the signalization data described above and answer the following questions:

1. Are neighborhoods with higher levels of protection safer for bikes and pedestrians?
2. Does the urban to suburban spectrum impact safety outcomes of left-turn signalization practices?
3. Is safety in the highest crash neighborhoods influenced by left-turn signalization?

To accomplish this, we first used GIS to aggregate the signalization data, street data, crash data, pedestrian and bicyclist commute mode share, intersection density, and residential density at the census block group level. For posted speed aggregated by census block group, we calculated the average posted speed of all streets within each census block group. Similarly, for AADT, we took the average AADT on all streets where AADT was recorded in the census block group.

We then sorted the census block groups into categories of protection level. Determining the thresholds to define each group proved challenging due to the uneven distribution of the data. Because over half of the census block groups in our sample had zero protected-only signals, the census block groups could not be split into even quartiles. Therefore, once the zero-protection group was excluded, the remaining three groups were sorted into three relatively similarly sized groups. Accordingly, we compared zero protection with low protection (defined as greater than zero and up to 16.7%, or one of every six signals is protected-only), medium level of protection (defined as over 16.7% and up to 33.3% of signals being protected-only), and high levels of protection (defined as census block groups with over 33.3% of their left-turn signal movements being protected-only).

In the next phase of analysis, we sought to break the groups into quartiles based on their relative level of urbanity to understand variation in crash rates and protection levels along the urban to suburban spectrum. To capture variation in crash rates based on contextual distinctions, census block groups were grouped into quartiles based on the number of intersections per square mile: high intersection density (over 244 intersections per square mile), high medium intersection density (Mid High ID= intersections of 179 to 244 per square mile), low medium intersection density (Mid-Low ID= intersections 108–179 intersections per square mile), and low intersection density (LID= interactions under 108 intersections per square mile). Then crash rates and protection levels were compared by neighborhood typology.

While the methods above helped to control for contextual factors in the built environment that may also impact crash risk, the issue remains that because crash history is another determining factor in left-turn signal warrants, census block groups with high protection may be predisposed to have higher crashes regardless of signalization. As such, the third phase of analysis looks at varying protection levels exclusively in the highest crash groups. To begin, we took the highest quartile of serious injury and fatality crashes (SI/fatal crashes greater than 10) and then divided them into the same context groups of high intersection density (HID defined as over 244 intersections per square mile), high medium intersection density (Mid-High ID 179 to 244), low medium intersection density (Mid-Low ID= intersections 108–179 intersections per square mile), and low intersection density (LID= interaction density under 108 intersections per square mile). Within each group we compared crash rates of high (defined as above average) and low protection level (defined as below average level of protection) to see if there were differences associated with the levels of protection within the high crash groups. We then applied a t-test to discern the level of statistical significance.

10. RESULTS

10.1 Are Neighborhoods with Higher Levels of Protection Safer for Bikes and Pedestrians?

While the observational nature of our study does not support any conclusions about cause and effect, our analysis in Table 10.1 suggests that neighborhoods with higher levels of protected left-turn phasing have higher crashes in almost every category examined, including pedestrian and bike serious injury and fatality crashes. However, consistent with our Part 1 findings, these block groups also had much higher AADT and much lower intersection density, suggesting that there may also be higher levels of vehicle exposure in these neighborhoods, which may also be increasing crash risk. In fact, when viewed as a rate of vehicle volumes, the neighborhoods with the higher levels of protected-only signalization appear safest. Considering that our study is primarily interested in bicyclist and pedestrian safety, measuring crashes per vehicle miles driven may be less appropriate than as a rate of population or bicyclist and pedestrian commuting mode share.

10.2 Does the Urban to Suburban Spectrum Impact Safety Outcomes of Left-Turn Signalization?

To further isolate some of the confounding variables, we next examine safety by protection level along the urban to suburban spectrum in Table 10.2. The results consistently show that neighborhoods with the lowest levels of protection had the lowest bicyclist and pedestrian serious injury and fatal crashes as a rate of population, but the discrepancy between lowest and highest protection neighborhoods is largest in the more suburban (lowest intersection density) neighborhoods. When viewing crashes as a rate of vehicle miles traveled (VMT), however, this trend reverses and neighborhoods with the lowest levels of protected left-turn signalization have the highest crash rates in all except for the most urban contexts where crash rates continue to rise with higher levels of protection. While we included the VMT exposure metric as a point of comparison, it is important to acknowledge that VMT is an inappropriate exposure metric for our study given our primary interest in understanding true risks to pedestrians and cyclists where population or mode share can better represent exposure.

Table 10.1 Crashes by Protection Level

	n	Average AADT	Avg. Posted Speed (mph)	Arterials (total miles)	Total Road Miles	Intersection Density (intersections per sq. mi.)	# Residents	# Pedestrian Commuters	# Bicyclist Commuters	Fatal or Severe Injury Crash Total	Fatal or Severe Injury Pedestrian/ Bicyclist Crash Total	Fatal or Severe Injury Crashes (per 1k residents)	Fatal or Severe Injury Pedestrian /Bicyclist Crashes (per 1k residents)	Fatal or Severe Injury Pedestrian/Bicyclist Crashes per bike/ped commuters (as percentage of population	Fatal or severe Injury Crash per 100,000,000 VMT	Fatal or Severe Injury Pedestrian or Bicyclist Crash per 100,000,000 VMT	Fatal or Severe Injury Pedestrian or Bicyclist Crash per 1 mile
No Protected Signals (0%)	653	6,787	25	1.1	5.6	202.2	1,308	37	8.4	4.5	1.2	5	1.1	0.2	7.0	2.2	0.3
Low Level of Protected Signals (>0% and ≤16.7%)	161	10,841	26	2.0	7.2	256.2	1,312	70	6.4	9.5	2.0	11	2.6	0.3	4.3	1.4	0.4
Medium Level of Protected Signals (>16.7% and ≤33%)	146	12,340	30	2.0	7.1	156.3	1,658	28	6.7	16.1	2.8	16	2.3	0.5	6.0	1.0	0.4
High Level of Protected Signals (>33%)	130	16,847	30	2.0	7.7	133.0	1,928	42	10.6	13.0	2.5	27	4.3	0.4	3.6	0.8	0.5

Table 10.2 Level of Protection Grouped by Intersection Density

	Low Intersection Density (≤108 per sq. mi.)			
	No Protected only Signals (0%)	Low Level of Protected Signals (>0% and ≤16.7%)	Medium level ((>16.7% and ≤33.33%)	High Level of Protected Signals (>33.33%)
n	128	31	50	67
AADT(Mean)	9,957.0	12,636.0	17,663.6	20,164.0
AADT(sum)	69,930.8	92,045.9	175,181.4	137,929.0
Protected	0%	10%	28%	53%
Avg. Posted Speed (mph)	28.0	29.0	32.6	32.8
Arterials (total miles)	2.3	2.9	3.3	2.7
Intersection Density (intersections per sq. mi.)	65.7	75.1	83.5	87.6
# Residents	1,621.0	1,771.7	1,905.3	2,317.0
# Pedestrian Commuters	32.3	22.2	26.3	51.4
# Bicyclist Commuters	4.4	2.7	5.4	9.9
Fatal or Severe Injury Crashes (per 1k residents)	11.6	17.6	26.0	44.7
Fatal or Severe Injury Crashes (per 100,000,000 VMT)	4.9	2.0	3.3	2.9
Fatal or Severe Injury Pedestrian/Bicyclist Crashes (per 1k residents)	0.5	2.0	2.8	6.8
Fatal or Severe Injury Pedestrian/Bicyclest Crash (per 1 mile road segment)	0.1	0.2	0.3	0.4
Fatal or Severe Injury Pedestrian/Bicyclist Crashes (per 100,000,000 VMT)	0.9	0.3	0.4	0.7
Fatal or Severe Injury Pedestrian/Bicyclist Crashes (per # of bikes and pedestrians)	0.2	0.5	0.6	0.6

	Low-Medium Intersection Density (>108 and ≤179 per sq. mi.)			
	No Protected Signals (0%)	Low Level of Protected Signals (>0% and ≤16.7%)	Medium (>16.7% and ≤33.3%)	High Level of Protected Signals (>33.3%)
n	152	40	49	31
AADT(Mean)	8,971.0	12,990.0	11,780.0	19,245.0
AADT(sum)	40,854.6	79,470.6	87,456.8	96,260.0
Protected	0%	9%	26%	54%
Avg. Posted Speed (mph)	26.0	27.4	29.0	29.7
Arterials (total miles)	1.0	1.6	1.4	1.2
Intersection Density (intersections per sq. mi.)	145.0	139.3	145.6	139.5
# Residents	1,387.5	1,312.0	1,719.8	1,640.0
# Pedestrian Commuters	28.6	33.7	24.7	22.5
# Bicyclist Commuters	6.6	6.4	5.3	7.1
Fatal or Severe Injury Crashes (per 1k residents)	4.1	8.7	10.0	7.5
Fatal or Severe Injury Crashes (per 100,000,000 VMT)	5.0	6.0	3.6	2.2
Fatal or Severe Injury Pedestrian/Bicyclist Crashes (per 1k residents)	1.0	2.1	2.0	1.5
Fatal or Severe Injury Pedestrian/Bicyclest Crash (per 1 mile road segment)	0.3	0.4	0.5	0.6
Fatal or Severe Injury Pedestrian/Bicyclist Crashes (per 100,000,000 VMT)	2.1	1.9	0.5	0.5
Fatal or Severe Injury Pedestrian/Bicyclist Crashes (per # of bikes and pedestrians)	0.3	0.5	0.6	0.3

	Medium-High Intersection Density (>179 per sq mile and ≤244 per sq. mi.)			
	No Protected Signals (0%)	Low Level of Protected Signals (>0% and ≤16.7%)	Medium Level (>16.7% and ≤33.3%)	High Level of Protected Signals (>33.3%)
n	188	34	29	19
AADT(Mean)	4,971.0	9,389.0	6,347.0	9,735.8
AADT(sum)	29,635.0	64,269.6	48,027.0	69,863.9
Protected	0%	10%	26%	55%
Avg. Posted Speed (mph)	24.2	24.7	27.7	26.9
Arterials (total miles)	0.8	1.7	1.1	1.1
Intersection Density (intersections per sq. mi.)	213.1	212.7	213.2	207.9
# Residents	1,254.9	1,267.8	1,359.8	1,439.7
# Pedestrian Commuters	39.0	72.9	18.9	52.4
# Bicyclist Commuters	9.8	7.7	5.6	20.4
Fatal or Severe Injury Crashes (per 1k residents)	4.0	5.7	11.3	6.0
Fatal or Severe Injury Crashes (per 100,000,000 VMT)	4.7	5.1	10.0	2.1
Fatal or Severe Injury Pedestrian/Bicyclist Crashes (per 1k residents)	1.4	1.9	2.3	1.4
Fatal or Severe Injury Pedestrian/Bicyclest Crash (per 1 mile road segment)	0.5	0.4	0.5	0.4
Fatal or Severe Injury Pedestrian/Bicyclist Crashes (per 100,000,000 VMT)	1.5	2.2	1.6	0.5
Fatal or Severe Injury Pedestrian/Bicyclist Crashes (per # of bikes and pedestrians)	0.3	0.3	0.4	0.2

	High Intersection Density (<244 per sq. mi.)			
	No Protected Signals (0%)	low Level of Protected Signals (>0% and ≤16.7%)	Medium level of Protected Signals (>16.7% and ≤33.3%)	High Level of Protected Signals (>33.3%)
n	185	56	18	13
AADT(Mean)	4,707.9	9,228.6	8,640.2	4,250.9
AADT(sum)	28,643.0	104,178.6	65,502.1	44,877.5
Protected	0%	10%	24%	46%
Avg. Posted Speed (mph)	23.3	24.7	26.3	24.9
Arterials (total miles)	0.6	2.0	1.1	1.0
Intersection Density (intersections per sq. mi.)	332.9	466.4	342.8	322.6
# Residents	1,081.0	1,086.0	1,282.0	1,324.7
# Pedestrian Commuters	43.7	120.6	52.0	22.7
# Bicyclist Commuters	11.3	7.7	15.9	7.5
Fatal or Severe Injury Crashes (per 1k residents)	3.4	11.5	10.1	10.3
Fatal or Severe Injury Crashes (per 100,000,000 VMT)	12.7	3.8	13.5	17.9
Fatal or Severe Injury Pedestrian/Bicyclist Crashes (per 1k residents)	1.2	3.8	2.0	2.2
Fatal or Severe Injury Pedestrian/Bicyclest Crash (per 1 mile road segment)	0.3	0.5	0.5	0.7
Fatal or Severe Injury Pedestrian/Bicyclist Crashes (per 100,000,000 VMT)	3.8	1.2	2.8	3.6
Fatal or Severe Injury Pedestrian/Bicyclist Crashes (per # of bikes and pedestrians)	0.3	0.3	0.2	0.4

10.3 Among the Highest Crash Neighborhoods Does Protected-Only Left Turn Signalization Impact Safety?

Our analysis in Part 10.1 and 10.2 suggests a positive association between high-crash neighborhoods and levels of protected-only left-turn signalization with levels of left-turn protected-only signals consistently higher in the highest crash census block groups along the urban to suburban spectrum.

The association of high crash census block groups with a higher percentages of protected-only left-turn signal phasing may make it appear as though protected-only left-turn phasing is more dangerous, but from the analysis in Part 1 of this report, we also know variables associated with higher crash risk often trigger the implementation of protected-only left-turn phasing, including an existing high crash history (ITE Florida Section, 1982; Agent, 1985; Yu, 2007). Accordingly, Table 10.3 looks at the highest crash quartile (in the bottom row of Table 10.3) to examine whether any trends emerge related to protection levels within this high crash group. Within the highest crash quartile (census block groups with the highest SI/fatal raw number of crashes), Table 10.4 examines above average protection and compared it with below average protection levels in each context category.

The results in Table 10.4 show that high left-turn protection is consistently associated with lower crash rates in all contexts except for the lowest intersection density locations and SI/fatal crashes in the medium high intersection density category. Incidentally, the spread between the two groups in terms of vehicle volumes, posted speed, and intersection density all narrowed substantially when examining protection level through the high crash lens, effectively controlling for other contextual features. Despite the consistent trends showing fewer crashes in the high protection groups, only bicyclist and pedestrian severe injury/fatalities as a rate of population in the highest intersection density category were found to be statistically significant.

Table 10.3 Protection Level by Intersection Density and Number of Serious Injury or Fatality Crashes

	Low Intersection Density (<108 per sq. mi.)	Low-Medium Intersection Density (>108 per sq. mi. and ≤179 per sq. mi.)	Medium-High Intersection Density (>179 and ≤244 per sq. mi.)	High Intersection Density (<244 per sq. mi.)
Lowest Crash Quartile Block Groups (≤1)	7.4%	4.5%	2.6%	0.9%
Low-Medium Crash Quartile Block Groups (>1 and ≤5)	17.0%	7.2%	8.2%	4.3%
Medium-High Crash Quartile Block Groups (>5 and ≤10)	20.2%	13.2%	7.5%	9.0%
Highest Crash Quartile Block Groups (>10)	27.3%	23.4%	15.5%	14.1%

Table 10.4 Signal Phasing Among the Highest Crash Quartile, *p value <.05

	Low Intersection Density (<108 per sq. mi.)		Low-Medium Intersection Density (>108 and ≤179 per sq. mi.)		Medium-High Intersection Density (>179 and ≤244 per sq. mi.)		High Intersection Density (<244 per sq. mi.)	
	High Crash Block Groups with Low Signal Protection	High Crash Block Groups with High Signal Protection	High Crash Block Groups with Low Signal Protection	High Crash Block Groups with High Signal Protection	High Crash Block Groups with Low Signal Protection	High Crash Block Groups with High Signal Protection	High Crash Block Groups with Low Signal Protection	High Crash Block Groups with High Signal Protection
n	45	50	31	35	30	23	29	19
% Protected Signals	10.0%	43.5%	6.0%	38.8%	1.5%	33.7%	3.9%	29.6%
AADT (mean)	15,807	19,916	10,704	14,531	2,558	2,911	6,497	3,186
AADT per mile	16,347	21,237	15,770	24,844	9,821	8,641	10,921	10,150
AADT (sum total)	177,755	161,421	107,905	119,808	70,771	53,220	107,739	60,906
Avg. Posted Speed (mph)	31	32	29	30	27	29	25	26
Arterials (total miles)	4.0	3.2	1.4	1.4	1.2	1.2	1.9	1.0
Highways (total miles)	2.8	3.2	1.1	0.6	1.3	1.4	0.6	1.2
Intersection Density (intersections per sq. mi.)	66.4	76.0	149.5	144.2	214.6	212.0	426.6	314.2
# Residents	2,200.6	2,298.9	1,540.5	1,674.5	1,671.4	1,374.9	1,176.0	1,463.0
# Pedestrian Commuters (as function of population)	27.9	31	34.5	25.0	71.9	39.5	88.2	19.0
# Bicyclist Commuters (as function of population	4.8	7.2	12.6	9.0	12.3	5.0	4.3	11.0
Fatal or Severe Injury Crashes (per 1k residents)	29.0	63.3	17.0	13.4	13.4	16.1	18.5	14.7
Fatal or Severe Injury Crashes (per 100,000,000 VMT)	2.9	4.5	5.3	3.4	12.1	11.9	51.0	20.9
Fatal or Severe Injury Pedestrian/Bicyclist Crashes (per 1k residents)	3.2	9.6	3.8	2.6	4.6	3.2	5.4*	2.7*
Fatal or Severe Injury Pedestrian/Bicyclist Crashes (per ped/bike commuters)	0.8	0.9	0.9	0.7	0.7	0.6	0.9	0.7
Fatal or Severe Injury Pedestrian/Bicyclist Crashes (per 100,000,000 VMT)	0.3	0.7	1.2	0.7	4.6	2.1	14.9	4.0
Fatal or Severe Injury Pedestrian/Bicyclist Crash (per 1 mile road segment)	0.3	0.6	0.9	0.9	1.8*	0.6*	0.8	0.8

11. CONCLUSIONS

Our study of left-turn signalization practices across 1,090 census block groups in four cities demonstrates that protected-only left-turn phasing use is atypical. Moreover, its application on streets and in neighborhoods where pedestrians and bicyclists are most likely to be remains even scarcer. Considering the existing research showing the safety benefits of uniformity in application (Yu, 2007), one might expect to see a more systematic approach to protected-only left-turn signal phasing. Yet, our results suggest protected-only left-turn signal phasing is typically applied as a spot treatment to mitigate other high-risk characteristics, which do not seem to include areas with high levels of active transportation. Thus, vulnerable road users remain routinely exposed to conflicts with left-turning vehicles across all four cities.

This naturally begs the question of whether current practice leads to worse safety outcomes, particularly for pedestrians and bicyclists in census block groups with higher levels of protected-only left-turn phasing.

Table 10.1 aggregates crashes at the census block group level to examine how system-level safety varies by protection level given the current state of practice. In general, Table 10.1 suggests that bicycle and pedestrian SI/fatal crashes are higher in census block groups with the highest protection levels. This trend persists when examining this question along the urban to suburban spectrum. While our results are insufficient to explain why this might be, we also find that these same census block groups tend to have higher posted speeds and higher total AADT, which further complicates the safety questions as these are also known crash risk factors (Hoye & Hesjevoll, 2020; Aarts, Letty, & Van Schagan, 2006). In fact, the crashes only appear to go down in census block groups with high protected-only left-turn signalization when considered as a rate of VMT, an inappropriate exposure metric for pedestrian- and bicyclist-involved crashes.

This current skewed application of protected-only left-turn phasing leaves us with an overall impression that places with more protected-only left-turn phasing are less safe. However, if the story was that simple, we would expect the trend of higher levels of protection associated with higher crash rates to continue even among the highest crash quartile of census block groups. Yet, our study largely found the opposite outside of the most suburban contexts (lowest intersection density). When comparing protection levels in the highest crash quartile, the crashes are consistently lower for bicyclists and pedestrians in the more urban census block groups when there is above average levels of protected-only left-turn phasing. While these results were not statistically significant, this trend suggests that protected left-turn signals may be somewhat protective for bike riders and pedestrians.

Given the contradictory results, making a broader generalization about safety remains confusing at best. We should also acknowledge the lack of a broader and more uniform application of protected-only signal phasing makes it difficult to conduct an apples-to-apples comparison of signalization practices with respect to safety that are not skewed by the high risk nature of their implementation in current practice. In other words, the existing landscape of signalization practices – where protected-only phasing seems to be implemented in response to high crash risk – makes it difficult to disentangle the safety impact of signalization from the larger context of where these signals tend to be placed. Future safety research would be enhanced by a broader and/or more uniform application of protected-only signal phasing. As such, future research should focus on how any shift in application of left-turn signal phasing practices impacts the safety of vulnerable road users when and if these practices take hold on a broader scale.

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PART 3: SIGNALIZATION PRACTICES & PEDESTRIAN CRASH SEVERITY AT INTERSECTIONS

13. INTRODUCTION

Crashes involving motor vehicles and pedestrians are increasing both in the United States and worldwide. Pedestrian fatalities as a percentage of all fatal motor vehicle crashes in the U.S. increased from 12.4% in 2006 to 18.8% in 2018 (NHTSA, 2020). Fatal and severe pedestrian outcomes (Levels 4 and 5 in Figure 13.1) constituted 30% of all pedestrian crashes in Colorado during this period.

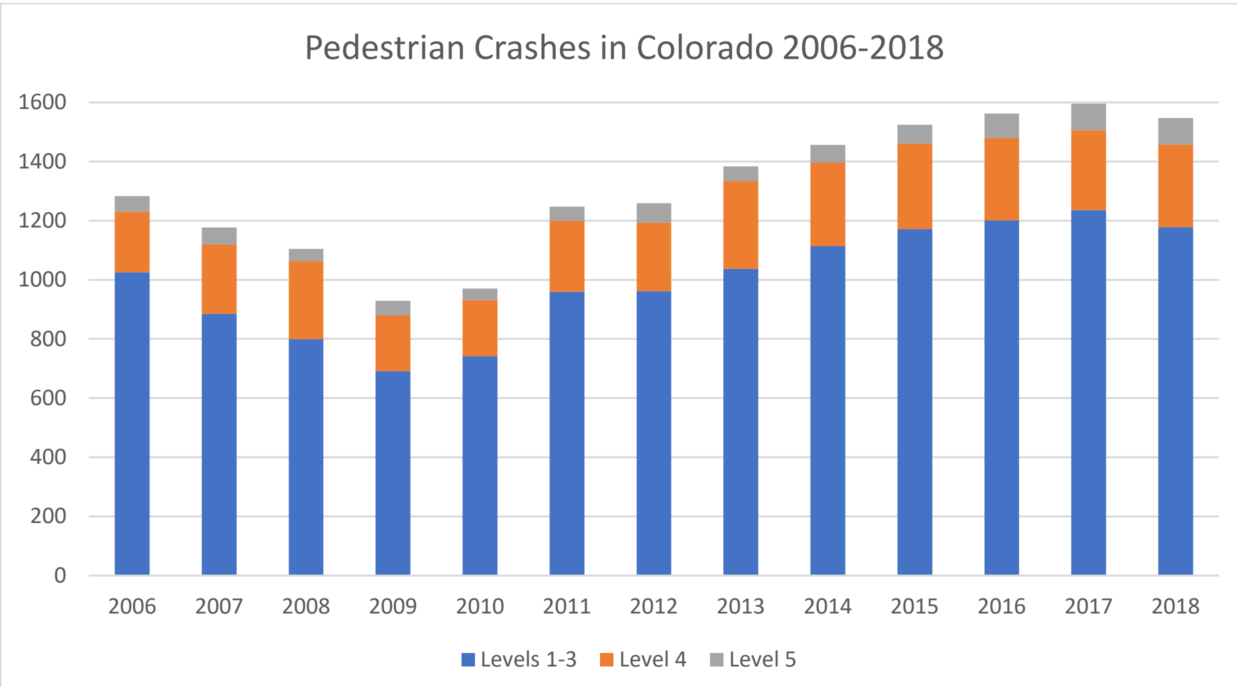

Figure 13.1 Pedestrians Crashes in Colorado by Year 2006 – 2018

Numerous studies have investigated factors associated with pedestrian crash frequencies or severities. These studies often analyze entire datasets of reported crashes without aggregating crash characteristics for specific locations (Montella et al., 2011; Islam & Jones, 2014; Uddin & Ahmed, 2018; Liu et al., 2019; Mukherjee D. & Mitra S., 2021; Guo et al., 2021; Mashhadi and Ksaibati, 2021). Some studies do include general intersection characteristics, but again without grouping the crash data by specific location (Haghighatpour & Moayedfar, 2014; Haleem et al., 2015; Rifatt et al., 2017; Xu et al., 2017; Kuskapan et al., 2022). This paper focuses on pedestrian crashes at intersections in Colorado from 2006 to 2018. The main objective is to determine whether percent severe crashes (PSC) at intersections are significantly associated with many of the same factors associated with pedestrian outcome severity in general. While it seems likely that this would be the case, we have not found other studies investigating this question. Our paper fills this gap by investigating what street and road user characteristics associate with the relative level of pedestrian crash severity at intersections. The results of this analysis support this hypothesis with easy to interpret coefficients from linear regression relating crash factors to PSC at intersections.

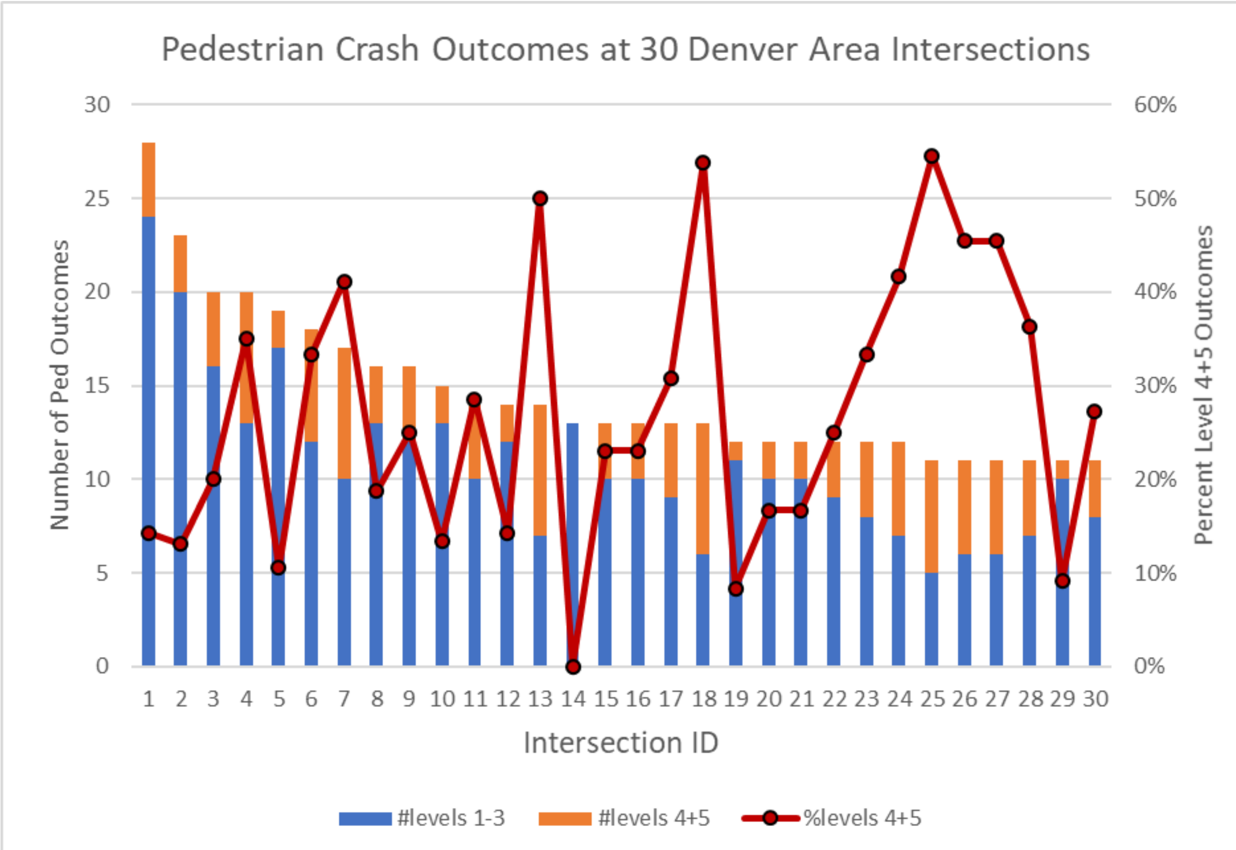

Figure 13.2 Pedestrians Intersection Crashes in Colorado by Year 2006 – 2018

Figure 13.2 shows the number of pedestrian crashes at 30 intersections in the Denver, Colorado, area with the highest number of pedestrian crashes from 2006 to 2018. The height of the stacked bar represents total crashes, which essentially equals total pedestrian outcomes because very few crashes involved multiple pedestrians. The numbers on the x-axis simply identify the intersection. The blue bars are numbers of less severe pedestrian outcomes (levels 1-3), and the orange bars are severe and fatal pedestrian outcomes (levels 4-5). The red line shows percent severe and fatal outcomes of total crashes with the scale shown on the right. The bar heights (crash frequencies) are related to traffic volumes (exposure levels) of both vehicles and pedestrians. However, the percentage of severe and fatal crashes is independent of exposure levels.

The red line shows how dramatically the PSC varies between intersections even though these intersections have similar roadway and traffic conditions. The question then arises as to whether variations in PSC can be partly explained by these crash characteristics at the intersections this study investigates. The motivation is to assist in targeting safety improvement resources on intersections of higher percent severity in addition to total crashes. In this paper, the term "severe" includes any crash resulting in a severe or fatal pedestrian outcome. Any pedestrian crash can result in serious injuries that might also lead to later complications. The terms "severe and less severe" are only used here to sub-divide these crashes into two groups.

14. BACKGROUND

From 2006 to 2018, as compiled by the Colorado Department of Transportation (CDOT), there were 17,047 reported crashes involving pedestrians and motor vehicles throughout Colorado. Although 10,384 of those crashes occurred at intersections, only 5,688 crashes also had the GPS coordinates needed to identify their locations. CDOT does include the names of the cross streets at the intersection of each crash, but these streets are keyed into the database with widely varying names. For example, Colfax Avenue may be coded as Colfax Ave E, Colfax St E, 3000 E Colfax Ave, Colfax St 3000 E, etc. Only GPS coordinates were used to identify intersection locations, and no additional matching of cross street names was attempted to increase the size of the dataset used in this analysis. This dataset was further reduced to 4,787 crashes at 2,578 different intersections because pedestrian outcomes for the other crashes were uncertain. Note that this analysis assumes that unreported crashes are proportional to total pedestrian crashes at each intersection such that the relative magnitudes of PSC between intersections would be unchanged if these crashes had been reported.

The CDOT dataset was chosen for this analysis because it is very comprehensive and consistent over many years. CDOT reports crash injuries as severity levels 1–5 corresponding to the KABCO injury ratings in reverse order. These are:

1 = O = no injury
2 = C = possible complaint of injury
3 = B = non-incapacitating injury
4 = A = incapacitating injury
5 = K = fatal

Among all 10,384 crashes at intersections, there were approximately 80% less severe injuries to pedestrians at levels 1–3 and 20% more severe injuries to pedestrians at levels 4 or 5. Among the reduced dataset of 4,787 pedestrian crashes at intersections, there were 3,900 (81.5%) less severe injuries to pedestrians at levels 2 or 3 and 887 (18.5%) more severe injuries to pedestrians at levels 4 or 5. These severity proportions indicate that the reduced dataset of known intersection locations and pedestrian outcomes have similar proportions to all reported pedestrian crashes in these years. Additionally, only 231 (4.8%) of 4,787 pedestrian crashes analyzed involved two or more pedestrians. In 70 (30%) of these 231 multi-pedestrian crashes, only one pedestrian outcome was known. In the other 161 multi-pedestrian crashes, the pedestrian outcome was randomly included in the analysis without consideration for severity. These 161 crashes were only 3.4% of the 4,787 crashes and thus would have a negligible effect on the analysis. Therefore, each crash has just one pedestrian outcome corresponding to it.

Since this paper’s objective is to analyze PSC at intersections, all intersections with only one pedestrian crash in the entire 2006 to 2018 period were removed. Intersections with only one crash do not represent crash outcomes as well because the PSC can only be 0% or 100% and that one crash may also have missing variable values. After removing all locations with just one crash, there remained 3,015 crashes at 806 different intersections (134 intersections with six or more crashes and 672 intersections with two to five crashes) to be analyzed.

A series of crosstabs were then computed for this dataset to tabulate the incidences of many variables reported for these crashes by intersection. These variables were selected based on our research and that of others (e.g., Guo et al., 2020; Billah et al., 2021) investigating their association with pedestrian crash severity. The variables tabulated into categories were:

1. Urban or rural area (0,1)
2. Lighting condition (daylight or non-daylight)
3. Vehicle movement (turning or going straight)
4. Vehicle speed (1–30 or 31–99 mph)

5. Speed limit of road vehicle is on (1–30 or 31–99 mph)
6. Vehicle type (passenger car or sport utility vehicle versus pickup or utility truck)
7. Driver gender (male or female)
8. Driver age (1–45 or 46–99 years old)
9. Driver impairment due to drugs or alcohol (yes or no)
10. Pedestrian gender (male or female)
11. Pedestrian age (1–45 or 46–99 years old)
12. Pedestrian impairment due to drugs or alcohol (yes or no)

The CDOT crash records include vehicle speed to the nearest 5 mph and the posted speed limit of the road on which the vehicle was traveling when the collision occurred. These values were first divided into five intervals (1–15, 16–30, 31–45, 46–60, and 61–99 mph) corresponding to the five predominant road classifications in Colorado, which are minor residential streets, residential arterials, commuting arterials, higher speed arterials, and freeway/interstate highways. Early comparisons of these groupings indicated the most significant difference in crash severity to occur above or below 30 mph for both the vehicle speed and the speed limit. This finding aligns with Tefft (2013), who found the risk of severe injury or fatality to reach 50% at 33.0 mph.

A similar analysis of pedestrian and driver ages showed the most significant difference in crash severity to occur above or below 45 years of age. Thus, these four variables were divided into the binary groupings listed above. Lighting condition and vehicle movement were also condensed from four categories down to two. One comment regarding vehicle type is that there were only 27 crashes involving larger combination trucks or buses among these crashes, so those 27 crashes were simply added to the truck category.

Many past studies have not included PUI (pedestrians under the influence of drugs or alcohol) in analyzing pedestrian crash frequency or severity. While the problem of DUI rates (driving under the influence) has long been addressed, the issue of PUI involvements has received far less attention. In Colorado from 2006 to 2018, a PUI was nearly three times as frequent as a DUI in pedestrian crashes with motor vehicles, and this multiple increases to 3.5 times for crashes with fatal or severe pedestrian outcomes. These multiples are also about the same for intersection related crashes and non-intersection crashes.

15. ANALYSIS

Table 15.1 lists the incidences of each variable listed above having a significant odds ratio computed both separately and the "adjusted" odds ratios from logistic regression. The number of crash outcomes shown for each variable in columns 2, 3, and 4 of Table 15.1 do not always sum to 3,015 because of missing values for that variable. Column 5 of Table 15.1 shows the severe and fatal outcome percentages within each factor level reported for these crashes.

Column 6 shows the unadjusted (or independent) odds ratio for each factor level compared with the base level listed first with no odds ratio shown. All variables in Table 1 are listed with the second factor level associated with greater severity. Thus, the odds ratios are all greater than 1. The null hypothesis of the odds ratio is that it is not significantly different from 1 based on the data, which is rejected if its confidence interval excludes 1 at the 95% level of confidence. Variables not listed had p-values above 5%. Columns 7–9 show the confidence interval bounds and z-statistic of each odds ratio, and column 10 shows the p-value of the z-statistic. Only vehicle type (with an unadjusted p-value of 13.9%) is still shown because it does become significant in logistic regression as shown later.

Vehicle speed has the greatest association to pedestrian crash severity when it exceeds 30 mph. Pedestrian age also affects resiliency to crash injuries. Possible reasons are physical durability and declines in sight or reaction time. Younger individuals can often recover from some critical injuries that would be fatal to older persons (Kim et al. 2008). Driver age, however, was not found in this study to significantly influence pedestrian outcome severity for any age groupings. As with pedestrians, driver age impacts how quickly they might be able to react to a potential collision, but older drivers may drive more cautiously and could be less likely to drive under the influence than younger drivers. Older drivers might be less often distracted by cell phones and other in-vehicle infotainment devices. These factors may compensate for any effects of slower reaction time or poorer vision of older drivers. It is difficult to know how drivers and pedestrians perceive and react in the split seconds before an impending crash occurs. Some factors such as lighting and a person's age and soberness are known to affect both a person's perception-reaction times and the person's ability to avoid a collision (Park & Bae, 2020).

Both driver and pedestrian impairment due to drugs or alcohol are very significant factors associated with pedestrian crash severity. The odds ratio for turning movement is also very significant, perhaps due to slower speeds of turning vehicles and the angle of impact. Urban versus rural was not significant because nearly all of these 3,015 crashes were at urban intersections. Three other variables (driver age, driver gender, and pedestrian gender) are also not shown in Table 1 because of not having significant odds ratios. While doing this research, logistic regression was applied to all pedestrian crashes in Colorado from 2006 to 2018, and the results were consistent with those reported by Batouli et al. (2020). Unlike Batouli et al., the current paper only analyzes crashes at intersections.

Logistic regression was next applied to these 3,015 crashes without reference to intersection location to identify variables with significant adjusted odds ratios of severe versus less severe pedestrian outcomes (Al-Ghamdi, 2002; Kleinbaum & Klein, 2010). Adjusted odds ratios from logistic regression are often lower (i.e., closer to 1) than the unadjusted odds ratios for the same factors because of correlations between variables. This effect can be seen by comparing the unadjusted and adjusted odds ratios for speed limit and average vehicle speed that are correlated. The opposite is true with the adjusted odds ratio being greater for vehicle type and pedestrian age, which are not correlated to any other variables. The difference is also affected by the number of observations being analyzed at each factor level. Thus, it is important to show the unadjusted odds ratios computed separately to reveal the effects of logistic regression on their values.

The next step of the analysis was to test which variables were significant in explaining percent severe crashes (PSC) at the 806 intersections having two or more pedestrian crashes. For each variable listed below, the average reported value was computed for crashes at each intersection as a continuous variable to be used in linear regression as listed below:

1. Lighting condition (% of crashes in non-daylight)
2. Vehicle movement (% of crashes going straight)
3. Vehicle speed (% of vehicles in crashes exceeding 30 mph)
4. Speed limit of road vehicle is on (% of speed limits exceeding 30 mph)
5. Vehicle type (% of vehicles in the truck category)
6. Driver gender (% male)
7. Driver age (% drivers exceeding 45 years of age)
8. Driver impairment due to drugs or alcohol (% impaired)
9. Pedestrian gender (% male)
10. Pedestrian age (% of pedestrians exceeding 45 years of age)
11. Pedestrian impairment due to drugs or alcohol (% impaired)

Table 15.2 lists the variables found to be significantly associated with percent severe crashes from linear regression. All variables found to be significant here were also found to be significant in the logistic regression in Table 15.1. No insignificant variables from logistic regression were found to be significant in the linear regression. Driver age and gender and pedestrian gender were not significant, as was true of the logistic regression results. The posted speed limit with a p-value of 18.3% was not significant because of its correlation with vehicle speed (it also had the weakest significance in Table 15.1). Vehicle speed was the most significant variable affecting PSC based on its coefficient size and significance level. Vehicle movement represented by percent turning vehicles in this model (which therefore has a negative coefficient) is also highly significant due to the slower speeds of turning vehicles and their angle of impact. Pedestrian age, pedestrian and driver impairment, and percent trucks all continue to be highly significant factors.

Figure 15.1 shows a graph of predicted versus observed PSC values for the same 30 Denver area intersections shown in Figure 13.2 with the most pedestrian crashes to occur during this analysis period. These 30 intersections have a correlation of 69% between the observed and predicted PSC values.

The linear regression model had an overall correlation of just 44% between the observed and predicted PSC values at all 806 intersections. This result is not surprising given how widely varying the PSC values are shown to be in Figure 13.2. The main objective of this study was to identify factors associated with this variation in PSC between intersections, which is indicated by the levels of significance shown for these variables.

Table 15.1 Pedestrian Crash Characteristics and Odds Ratios

					Computed Separately for Each Factor (Unadjusted)						Logistic Regression Model (Adjusted)			
Factor Level	Levels 4+5	Levels 1–3	Levels All	%4+5	Odds Ratio	Lower 95% CI	Upper 95% CI	z-stat	p-value	Signif	Odds Ratio	Lower 95% CI	Upper 95% CI	p-value
Lighting Condition														
Daylight	266	1,521	1,787	14.9%	*	*	*	*	*	*	*	*	*	*
Non-Daylight	316	912	1,228	25.7%	1.98	1.65	2.38	7.34	0.000	p<0.05	1.340	1.091	1.645	0.005
Speed Limit (mph)														
(1–30)	155	891	1,046	14.8%	*	*	*	*	*	*	*	*	*	*
(31–99)	392	1,341	1,733	22.6%	1.68	1.37	2.06	4.98	0.000	p<0.05	1.225	0.980	1.532	0.075
Vehicle Speed (mph)														
(1–30)	324	1,805	2,129	15.2%	*	*	*	*	*	*				
(31–99)	159	184	343	46.4%	4.81	3.78	6.14	12.68	0.000	p<0.05	2.675	2.002	3.574	0.000
Vehicle Movement														
Making Turn	227	1,591	1,818	12.5%	*	*	*	*	*	*				*
Going Straight	327	717	1,044	31.3%	3.20	2.64	3.87	11.93	0.000	p<0.05	2.045	1.630	2.567	0.000
Vehicle Type														
Pass Car/Van	421	1,766	2,187	19.3%	*	*	*	*	*	*				*
Pickup/Utility	118	416	534	22.1%	1.19	0.94	1.50	1.48	0.139	p<0.15	1.354	1.058	1.734	0.016
Pedestrian Age														
(1–45)	309	1,399	1,708	18.1%	*	*	*	*	*	*				*
(46–99)	243	687	930	26.1%	1.60	1.32	1.94	4.83	0.000	p<0.05	1.695	1.381	2.081	0.000
Ped Impairment														
No Impairment	482	2,288	2,770	17.4%	*	*	*	*	*	*				*
Alcohol/Drugs	100	145	245	40.8%	3.27	2.49	4.30	8.51	0.000	p<0.05	1.993	1.472	2.698	0.000
Driver Impairment														
No Impairment	553	2,396	2,949	18.8%	*	*	*	*	*	*				*
Alcohol/Drugs	29	37	66	43.9%	3.40	2.07	5.57	4.84	0.000	p<0.05	1.895	1.084	3.311	0.025

Table 15.2 Linear Regression Coefficients for Percent Severe Crashes at Intersections

Term	Coef	Std. Error	t-stat	p-value	Signif
Constant	0.168	0.036	4.68	0.000	
% non-daylight	0.057	0.033	1.76	0.078	p<0.10
% speed limit > 30	0.036	0.027	1.33	0.183	NS
% vehicle speed > 30	0.301	0.046	6.62	0.000	p<0.05
% turning vehicles	-0.098	0.034	-2.93	0.003	p=0.05
% PU + utility trucks	0.090	0.038	2.38	0.017	p<0.05
% ped ages > 45	0.055	0.029	1.87	0.062	p<0.10
% peds impaired	0.146	0.064	2.27	0.023	p<0.05
% drivers impaired	0.248	0.097	2.56	0.011	p<0.05

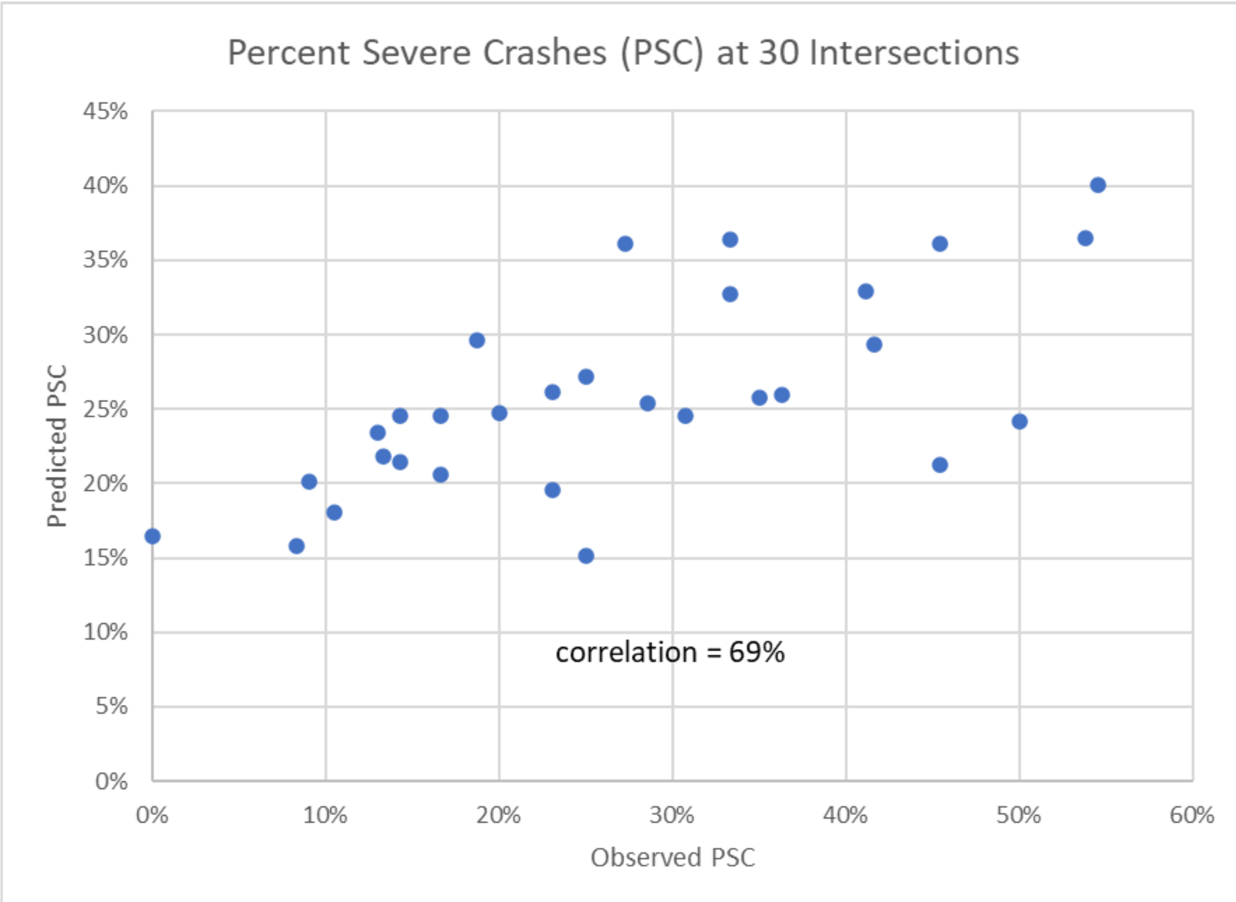

Figure 15.1 Predicted versus Observed PSC at 30 Denver Area Intersections

16. DISCUSSION

Given the previous discussion comparing the linear regression results to the logistic regression results, how can both results be used to estimate potential severe crash reductions from mitigating actions? One example is to estimate the potential reduction in severe and fatal crashes by reducing the vehicle speeds exceeding 30 mph in these crashes to below that level. The linear regression coefficient is 0.301 for percent vehicle speeds above 30 mph, as shown in Table 15.2. Table 15.1 shows that 343 (or 13.9%) of the 2,472 reported vehicle speeds exceeded 30 mph. Thus, multiplying 343 crashes by 0.301 yields a potential reduction of 103 severe or fatal crashes just among these 2,472 crashes with reported vehicle speeds. There were 10,384 pedestrian crashes at intersections throughout Colorado during this analysis period. This same estimate applied proportionally to all 10,384 crashes yields a potential reduction of 435 severe or fatal pedestrian crashes if crash vehicle speeds exceeding 30 mph could be reduced. Measures to bring about this speed reduction such as speed warning signs, enforcement, and public messaging would also reduce some of the vehicle speeds already within 30 mph, thus lowering the number of severe or fatal crashes even further.

A similar estimate can be made by using the logistic regression results, as explained by Batouli et al. (2020). Their approach requires calculating an effectiveness factor from the risk ratio and then applying it to the number of severe or fatal crashes at the worse factor level of a given variable of interest. The odds ratio of 2.675 shown in Table 15.1 corresponds to a risk ratio of 2.306 for vehicle speeds, which in turn results in an effectiveness factor of 0.566 or 56.6%. This effectiveness factor is multiplied by the 159 fatal or severe crashes with vehicle speeds exceeding 30 mph, which yields a potential reduction of 90 severe or fatal crashes just among the 2,472 crashes with reported vehicle speeds. Although the estimate of 90 fewer severe or fatal crashes is below the estimate from the linear regression results, it is reassuring to see that the two approaches yield similar estimates. The logistic regression estimate is slightly more conservative because it is applied directly to known fatal and severe outcomes.

The point elasticity of the logistic regression vehicle speed factor is 0.263 versus 0.301 for the linear regression equation. However, the linear regression model provides a much simpler way of estimating potential safety improvement impacts to percent severe crashes at intersections. The linear regression model can also be easily modified to retain the original integer values for pedestrian age, vehicle speed, and the posted speed limit. That approach was tested in this research and yields similar results to the linear regression model described above, but it was not included here so as to show consistency with the logistic regression results. Other non-linear forms of the regression model were also tested but with only marginally different results.

17. CONCLUSION

As stated in the introduction, numerous studies have analyzed reported crashes without aggregating the crash characteristics for specific locations. The objective of this paper was to determine whether percent severe crashes (PSC) at intersections specifically are significantly associated with many of the same factors associated with pedestrian outcome severity in general. The most significant variables associated with fatal and severe injury pedestrian crash percentages at intersections were found to be lighting conditions, vehicle speed, a vehicle's turning movement, vehicle type, pedestrian age, and driver or pedestrian impairment by drugs or alcohol. The findings also suggest that pedestrian impairment also needs attention in addition to driver impairment and vehicle speeds in efforts to reduce pedestrian crashes and their severity.

Non-daylight conditions, which include dawn and dusk when sun glare can be a problem, were found to be significantly associated with severe and fatal pedestrian outcomes as was found by many previous studies (Donnell et al., 2010; Jackett & Frith, 2013; Sullivan & Flannagan, 2007; Bullough et al., 2013). New technologies are being developed to improve the in-vehicle detection of pedestrians and bicyclists to drivers. Wearable devices and reflective clothing are also being improved to increase pedestrian visibility by way of better illumination and reflectivity. Thus, many new and conventional countermeasures such as lowering speed limits can be considered in combination to improve safety at intersections found to have higher PSC.

A key research challenge has been the historic overemphasis on metrics such level of service and reducing vehicle delay. This prioritization seems to undermine safety for pedestrians and bicyclists who face greater risks when left-turning vehicles are given permissive signals and has, in part, led to few fully protected intersections.

We recommend the next steps to be expanding the research to include safety analysis at the limited sites where protected-only left-turn signalization is used. Even with sparse crash data, conflict analysis from video footage could help identify near-misses and interactions between left-turning vehicles and pedestrians, providing valuable insights into safety benefits. We should also explore how pedestrian and bicyclist movements change in response to different signalization strategies.

Future research should continue pushing for a shift toward safety-focused intersection designs, reducing the disproportionate focus on vehicle efficiency versus the safety of vulnerable road users. Developing better safety metrics and revising signalization standards based on safety outcomes rather than traffic flow will be critical in reshaping our streets.

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19. APPENDIX A. CLASS PROJECT ASSIGNMENT

Scenario No. 6: Integrating Rapid Response into a Reimagined Vision Zero
CVEN 5662: Transportation System Safety with Dr. Wes Marshall

THE MARSHALL FOUNDATION REQUEST FOR PROPOSALS

Your city has finally come to realize that safety on our streets is not as much about reducing the number of fender benders as it is about eliminating fatalities and severe injuries. In a more perfect world, your city would set about making each and every street and intersection safer, but this is too high of a hurdle – both economically and politically – for almost every city at this point.

Instead, your city officials are working on a Vision Zero plan that will propose:

- a couple protected bike lanes,
- increasing police enforcement of all modes, and
- an education program about distracted driving and distracted walking.

If those things come to fruition, your city may be a little bit safer. Will it be significantly closer to eliminating fatalities and severe injuries? Not a chance.

The Marshall Foundation aims to improve transportation safety by providing cities with a more definitive place to start. With a $100 million budget, the Foundation will fund one proposal that takes a 'safe systems' approach and focuses our efforts on a crash type that we tend to overlook because we chalk it up to human error. Under a safe systems mindset, crashes often erroneously get blamed on 'human error' when the underlying problem is systemic to the transportation system itself. Here is what the Marshall Foundation is looking for:

- Your first task is to describe a single crash type that we attribute to 'human error' but that engineers and planners could have some control over.
- Next, find at least one real-life local example of this crash type resulting in a fatality or severe injury and try to get yourself a copy of the police report.
- Then, perform and document something akin to Denver's Rapid Response program approach to analyzing that crash.
- Document and consider your intervention alternatives for the location where your crash happened. What are the advantages and disadvantages of each?
- Use crash data for your selected city to show how extensive this issue might be and the benefits of solving it.
- Now reconsider your intervention alternatives for use at the city scale. What are the advantages and disadvantages of each when trying to solve this crash type across the entire city?
- Lastly, develop an intervention plan for addressing this underlying, systemic design issue at the city scale.

Proposals should include the following:

- Cover letter;
- Executive Summary (300 words max);
- Project Narrative (no more than 20 pages of double-spaced text; figures, tables, site photos, and references do not count towards the total);
- Very rough Cost Estimate of safety intervention plan; and
- Project Infographic (visually highlighting the problem and solutions).

This is an individual assignment.

Proposal Scoring *(100 Points Max):*

Initial Thoughts = *10 Points*
Executive Summary = *10 Points*
Project Narrative = *30 Points*
Project Infographic = *25 Points*
Project Presentation = *25 Points*

You have three weeks to conduct your investigation, upon which you will submit your proposal via Canvas. Later that night, you will give a 20-minute presentation to the class.

Before the end of Wednesday, please read and analyze this assignment and turn in a document that answers to following:

- What do I already know about these issues?
- What questions do I need to answer?
- What do I need to learn about to do so?
- What is my initial plan of action?
- What list of resources do I expect to be useful?

Over the next couple weeks, we will reconvene so that everybody can provide a project update. You are welcome to discuss your work and provide assistance to others in the class; however, your proposal and presentation should be your own work. Also, please be sure to properly cite all sources. If you are unsure about whether you need to cite something, it is better to err on the side of citing too much rather than too little…

Also note that there are plenty of free infographic websites that will help you in the creation of that requirement.

On Monday, December 4th, everybody will hand out their infographics (bring enough copies for everyone) and present their findings. Please limit your presentation to 20 minutes.

The proposal should be uploaded to Canvas by 10 AM on December 4th, and the presentation should be uploaded by 4 PM on the same day.

VISION ZERO

20. APPENDIX B. EXAMPLES OF STUDENT WORK

Vision Zero Proposal

Executive Summary:

Among transportation professionals there is an often-cited statistic that 94% of crashes are caused by human error. Left turn crashes are one such crash type. Often chalked up to errors such as failure to yield or distracted driving, the relatively simple interventions in the built environment have gone largely overlooked.

We propose taking an alternate approach that examines the underlying contributing factors in the built environment to more effectively reduce serious injury and fatalities related to left turn crashes. The summary report examines left turn crash data in Denver to better understand the relationship between the often-cited human factors and contributing factors that can be better addressed through a system level analysis of the built environment. First, we look at what can be gleaned from the data on serious injury and fatality left turn crashes, and then we take a deeper dive into shared characteristics in the built environment. Finally, this report seeks to examine various alternative approaches to addressing the far too common left turn crash that Denver can use as a starting point to achieve vision zero. By acknowledging the role that design and engineering play in errors such as failure to yield our approach has the potential to finally make a dent in one of the most common crash types.

Project Narrative:

Data analysis:

Left turn crashes represent one of the most common crash types that lead to serious injuries and fatalities in in the City and County of Denver. While representing 10.3% of the total crashes, of serious injury and fatalities in Denver, 28.7% involved left turn movements. Just over half of the serious injury and fatality left turn crashes cited some type of human error in the crash including distracted driving and failure to yield the right of way. Of the human errors involved in left turn serious injury and fatality crashes, aggressive driving was the most common followed by distracted driving. However, each are a relatively small share of the total, leaving few answers on clear solutions.

Issues with the Human Error approach:

While human error is often cited in crashes, the range of human error types is varied. Aggressive driving, distracted driving, careless driving, driving under the influence and failure to yield are all commonly cited errors in left turn crash data. Given the range of human errors cited, no single human error cause emerges as a clear answer, with each taking a nominal share of the total. Accordingly, starting from the question of what human errors lead to left turn crashes leaves few clear answers on how to eliminate such crashes, and is unlikely to lead to effective solutions.

Looking at the data on each human error individually leads to equally confusing conclusions as they relate to left turn crashes. Of serious injury and fatality crashes where distracted driving was cited as a human error, left turn crashes account for 29.76% distracted driving serious injury and fatality crashes[1]. Similarly, of cases where aggressive driving was cited, left turns account for 32.4%[2]. Of crashes where driver inexperience was cited, 31.12% were left turn crashes[3]. Another error cited in many crashes is failure to yield. Left turns account for 36.4% of failure to yield crashes[4].

Interestingly, "no apparent" human error was cited in nearly 30% of left turn crashes, far more than the individual human error types, lending further support to the importance of looking beyond human errors[5] in safety strategies.

Given the mixed results of the human error analysis, it's not surprising that a focus on human errors in safety strategies leads to few clear answers. Furthermore, even if one clear human error came through as a primary cause, it's unclear how the tools at the city's disposal such as education and enforcement could move the needle substantially at a system level scale given the track record.

Yet conversations around safety continue to revolve around policies that address behavior. Distracted driving has become an increasingly common refrain in safety conversations. SB22-175 that was recently introduced in the Colorado legislature, for example, suggests cracking down on distracted driving to reduce crash rates.

A Better Approach:

[1] Traffic Accidents, Open Data, City and County of Denver
[2] Traffic Accidents, Open Data, City and County of Denver
[3] Traffic Accidents, Open Data, City and County of Denver
[4] Traffic Accidents, Open Data, City and County of Denver
[5] Traffic Accidents, Open Data, City and County of Denver

Considering the mixed bag of human errors involved in left turn crashes, it is our position that taking an approach that focuses on the common built environment factors among all left turn crashes leads to a clearer path forward. While various human factors may have been involved, regardless of whether the driver was aggressive, inexperienced, or distracted, they all traverse similar sets of obstacles in approaching a left turn due to design and engineering. Design and engineering are also factors that are substantially within the public's control. Therefore, looking at strategies that focus on factors in the built environment have the potential to address left turn crashes at a system level scale.

To examine built environment factors, we identified patterns with regard to road type and road characteristics involved in the left turn crashes.

Facility characteristics: Astonishingly, 83.4% of left turn crashes occurred on streets designated as arterials, and 71% were on roads of four or more lanes[6]. 47.7% of fatal and serious injury crashes occurred on one-way streets[7]. Not surprisingly, there is also a trend with regard to posted speeds with 55% occurring on streets having a posted speed of 35mph or more[8] (84% were on streets of 30mph or more).

The data also reveals compelling patterns with regard to crash location on such facilities. Sixty-two percent of Denver's serious injury and fatality left turn crashes occurred at signalized intersections[9].

Who is impacted: Our preliminary data analysis revealed that active transportation modes are disproportionately impacted by left turn crashes.

Overall bikes and pedestrians were only involved in 2.8% of all crashes, but pedestrians and bicycles were involved in 24.4% or 155 (101 pedestrians and 54 bicycle) of the serious injury and fatality left turn crashes[10]. One hundred and fifteen of the bike and pedestrian accidents were at signalized intersections, 93% of which occurred at signalized intersections on arterials[11]. In total 131 of the left turn crashes involving bikes and pedestrians were on arterials. Over half of the left turn crashes where pedestrians and bicyclists were involved occurred on one-way streets.

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[6] Streets centerline, Open Data, City and County of Denver
[7] Traffic accidents and Street Centerline, Open Data Catalog, City and County of Denver
[8] Ibid
[9] Traffic Signals and Traffic Accidents, Open Data Catalog, City and County of Denver
[10] Traffic Accidents, Open Data Catalog, City and County of Denver
[11] Traffic Signals and Traffic Accidents, Open Data Catalog, City and County of Denver

Of note only 5 of the 101 crashes where a pedestrian was involved cited pedestrian violation of crossing against the signal in the crashes[12].

Given how extensive left turn crashes are overall, and the fact that they disproportionately impact vulnerable road users who are crossing appropriately at signalized intersections, addressing left turn crashes at signalized intersections represents an opportunity to make a large dent in Denver's most severe crashes.

How the patterns above relate to human error: With the permissive left turn phasing that currently prevails in Denver (roughly 70-80% of signals), drivers preparing for a left turn maneuver must watch both for a break in oncoming traffic (which in many cases consist of two or more lanes) and pedestrians and bicycles that may be approaching from both directions. The greater the number of lanes and the higher the speeds of oncoming traffic, the more difficult such a maneuver becomes. This is consistent with the crash data above that reveals the crash type was much more common on arterials with four or more lanes of traffic, and on streets with a posted speed over 35mph. Given high speeds and multiple lanes of high volumes of oncoming traffic, it would take little distraction to lead to an error in judgment of a driver determining when to turn left.

Potential Interventions:

Signal interventions: Given the sizable portion of crashes that occur at signalized intersections, it is our position that Denver's Vision Zero strategy should begin by addressing the signal phasing. Not only would this be a strategy that could be implemented efficiently on a broad scale, but it also could be achieved at a relatively low cost given how much can be done with software upgrades to Denver's existing assets. However, currently, the vast majority of Denver's signals operate with permissive left turn phasing with the basic three section signal heads, so there also would be a fair number of cabinet and signal head upgrades needed.

However, compared to other interventions, the cost of such upgrades would be relatively low compared to the systemwide benefits that the phasing changes could entail.

With the permissive left turn phasing that currently predominates among Denver's signals, drivers preparing for a left turn maneuver must watch both for a break in oncoming traffic (which in many cases consist of two or more lanes) and pedestrians and bicycles that may be approaching from both directions. The greater the number of lanes and the higher the speeds of oncoming traffic, the more difficult such a maneuver becomes. Therefore, we suggest beginning with upgrades on all arterials to eliminate permissive and protected/permissive left turns. We suggest at the very least implementing protected left turns only, with the timing such, that oncoming vehicle traffic, pedestrians and cyclists are not phased concurrently with opposing left turn traffic. While protected left turns would go a long way to improving the safety of drivers, pedestrians, and bicyclists, it may also lead to more congestion, particularly at

[12] Ibid.

peak travel times. Therefore, this would also require a shift in the city's priorities to fully embrace and take ownership of its Vision Zero commitment.

Another option would be to ban left turns at signalized intersections on arterials using existing signals, signage (at intersections using 3 ball signal heads only) and other reinforcing design elements. While this may also be an effective approach without requiring upgraded signal heads, it would require reinforcing design elements such as bollards or medians to ensure vehicle compliance. Another issue that may arise with this approach could be migration to increase the number of right turn crashes, which could lead to greater risks for vulnerable road users such as pedestrians and bicyclists.

It's also important to note the potential for using special pedestrian phasing such as leading pedestrian intervals, which the city has already begun implementing at intersections using permissive phasing. While in some cases the lead does give pedestrians an opportunity to get out far enough into the intersection to be visible, we do not recommend any approach that does not eliminate the conflict with left turns.

Aside from protecting vulnerable users by eliminating left turn conflicts through rephasing, signal installation can also be used to to protect pedestrians and other vulnerable road users by providing safer alternatives to intersection crossings by adding crosswalks and HAWK or RRFB's at midblock locations to offer alternatives to the high conflict intersections. In addition to reducing crossing distances and conflicts with turning vehicles, this approach would also help with traffic calming. Again, another drawback of this approach would be increased congestion however, if alternate modes are not sufficient.

Speed interventions: While the high posted speeds also clearly played a role in the left turn crashes, finding an appropriate intervention is less straight forward given the wide, expansive nature of arterials. A start, however, would be to lower the posted speeds on arterials where the speed limit is 35 mph or more given the large share of left turn crashes. Unfortunately, the signage alone is unlikely to be effective without also reinforcing the lower speed limits with traffic calming. While the interventions suggested above, will likely create congestion that may calm traffic during peak periods, additional interventions such as road resizing, and lane narrowing would also be needed to effectively slow traffic.

Road Size interventions: Given the large portion of left turn crashes occurring on arterials of four or more lanes, strategies that focus on reducing the number of general purpose lanes and overall width of the roadway may also be effective in reducing this crash type. In addition to reinforcing slower speeds, narrowing the general purpose travel way also makes for fewer conflicting vehicles for left turn maneuvers. Reducing the number of general purpose lanes could also have other co-benefits by freeing up more space for improved and enhanced pedestrian and bike facilities or even for dedicated transit lanes.

Additionally, "road diets" in some cases can be done at relatively low cost requiring little more than restriping for the basic configuration. However, to ensure slower speeds and better pedestrian and bike facilities, we suggest an approach that also implements streetscaping, and facilities that separate modes. Such improvements however would require more aggressive interventions involving construction.

A potential disadvantage to this approach could be increased congestion, especially if this were done in conjunction with the phasing interventions. However, if implemented along with investments that improve alternatives such as transit efficiency, and bike, pedestrian safety, this strategy also has the potential to improve congestion overall.

Therefore, we suggest examining scenarios that expand dedicated transit, bike, and pedestrian travel ways, and reduce general purpose lanes to no more than one way in each direction.

Intersection Interventions: Another alternative would be to reconstruct signalized intersections into roundabouts. While reconstructing all of Denver's 19,000 intersections would be cost prohibitive, roundabouts potentially eliminate left turn conflicts at intersections, would effectively eliminate left turn crashes. Therefore, roundabouts should be considered at strategic locations. However, if roundabouts were implemented on arterials as they exist today with four or more lanes of traffic, they likely will still have unsafe and difficult conditions given high speeds and lane changes that they may encourage. Therefore, they should only be implemented where traffic has been calmed and lanes reduced or for newly constructed or reconstructed intersections.

Vision Zero Intervention Plan:

Phase 1: Signal Intervention ($30M) Denver has a total of 1,288 traffic signals with the majority (1,047) on arterials. While upgrading all would be a giant undertaking, we recommend beginning with the 836 signals along streets with four or more lanes. Assuming that approximately 60% will require full upgrades we estimate a cost of approximately $25M. The remaining signals requiring partial, or software upgrades will cost approximately $5M.

Phase 1: Speeds: To replace the posted speed limit signs citywide on arterials we estimate a total cost of $1M. However, this step will have little impact without additional measures to calm traffic.

Phase 2: Strategic road resizing ($23.6 M) FHWA estimates a cost of $100,000 per lane mile for the standard road diet, but when done in conjunction with resurfacing it can be implemented at a fraction of the cost ($45,000 vs. $100,000). There are approximately 236 lane miles of arterial roadway in Denver. Assuming that a portion of this can be done along with the planned resurfacing we suggest the remainder be used for traffic calming amenities and median refuge islands.

Phase 2: Strategic placement of Midblock Pedestrian crossings with Hawk Signals: ($10M): Conduct study and add pedestrian midblock crossings to improve pedestrian safety by reducing conflicts inherent in intersection crossings and to reduce overall travel distance.

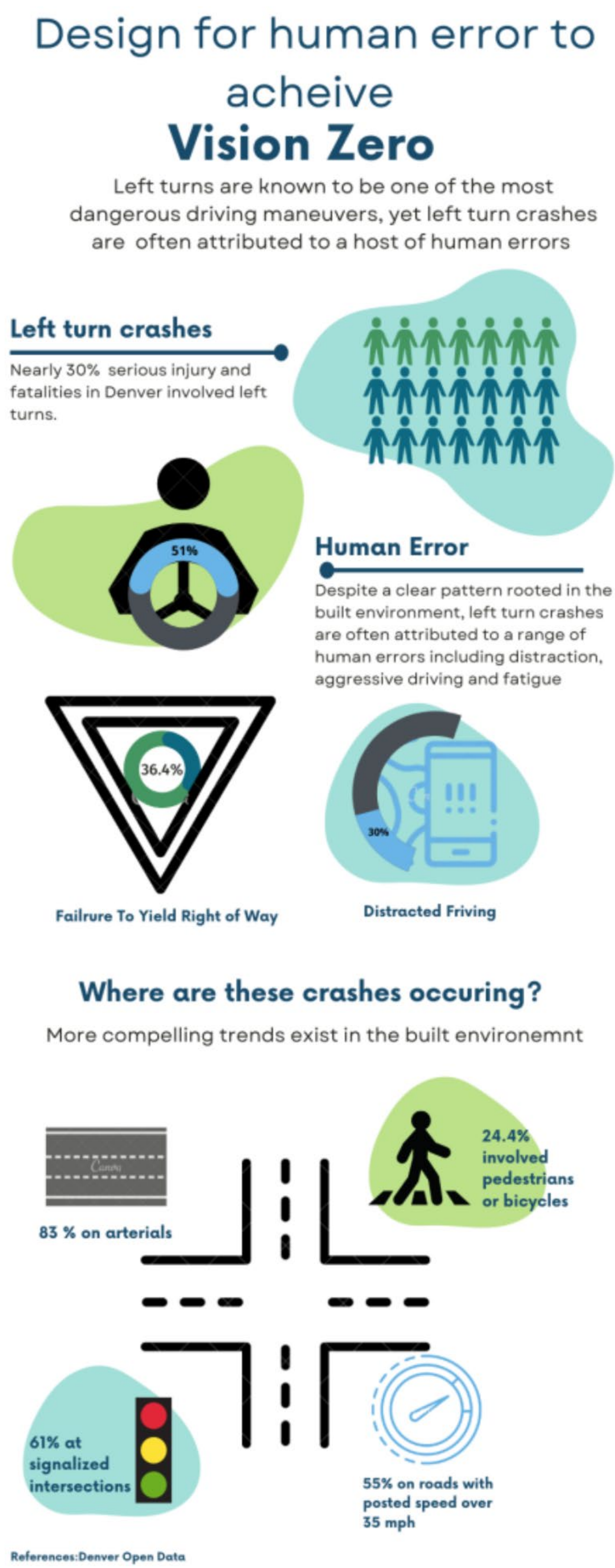
Phase 2: Strategic roundabouts ($30 M): conduct study to determine best location for 10 roundabouts, and then implement roundabouts based on study recommendations.

References:

City and County of Denver Open Data Catalog, Street Centerline, https://www.denvergov.org/opendata/dataset/city-and-county-of-denver-street-centerline. Viewed April 30, 2022

City and County of Denver Open Data Catalog, Traffic Accidents, https://www.denvergov.org/opendata/dataset/city-and-county-of-denver-traffic-accidents. Accessed, April 26, 2022

City and County of Denver Open Data Catalog, Traffic Signals, https://www.denvergov.org/opendata/dataset/city-and-county-of-denver-traffic-signals. Accessed April 30, 2022


Design for human error to acheive
Vision Zero
Left turns are known to be one of the most dangerous driving maneuvers, yet left turn crashes are often attributed to a host of human errors
Left turn crashes
Nearly 30% serious injury and fatalities in Denver involved left turns.
51%
Human Error
Despite a clear pattern rooted in the built environment, left turn crashes are often attributed to a range of human errors including distraction, aggressive driving and fatigue
36.4%
30%
Failrure To Yield Right of Way
Distracted Friving
Where are these crashes occuring?
More compelling trends exist in the built environemnt
83 % on arterials
24.4% involved pedestrians or bicycles
61% at signalized intersections
55% on roads with posted speed over 35 mph
References:Denver Open Data

Introduction & Purpose

The city of Denver officially committed to Vision Zero in 2016 under the Hancock Administration. This commitment aims to entirely eliminate roadway traffic deaths on Denver's streets. Through this commitment, the city of Denver's acknowledges core vision zero principles, such as the beliefs that any deaths on Denver's roadways are unacceptable, and preventable. However, there has been a steady increase in traffic deaths since Denver committed to vision zero, including pedestrian & bicyclists' deaths, as shown in figure 1.

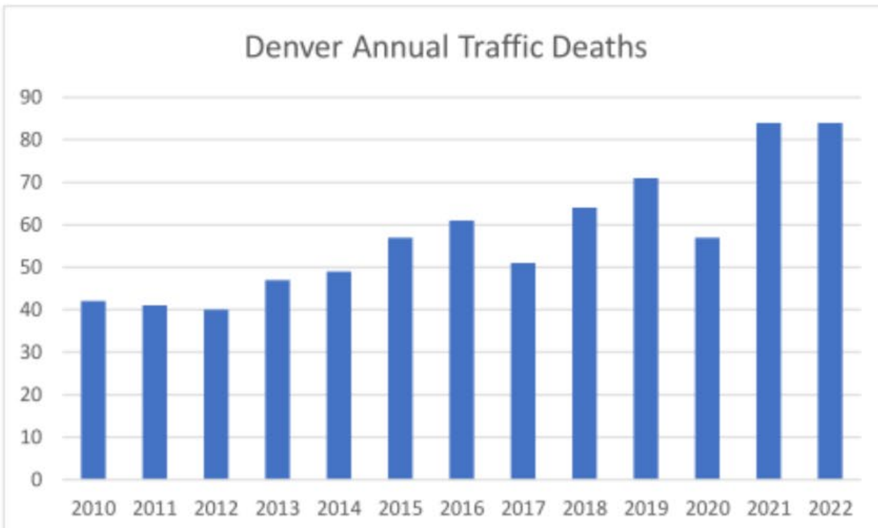


Figure 1: Denver Annual Traffic Deaths

Executive Summary

Given the rise in roadway deaths, it is clear that Denver must change its approach to vision zero. Instead of relying on the traditional pillars of sporadic integration of safety measures, enforcement, end education, vision zero must be approached with a Safe Systems Approach. This safe systems approach acknowledges that that human error is inevitable, but that the severe consequences of human error can be reduced by prioritizing safe transportation infrastructure. This system also approaches traffic safety as a systematic issue, that is that instead of only applying safety treatments at intersections & roads where deaths occur, the goal is to systematically eliminate opportunities for roadway deaths to happen in the first place. The goal is to create a city-wide environment where all road users, specifically pedestrians and bicyclists, are safe through design. This approach acknowledges that while human error can be unpredictable and inevitable, it should not result in the loss of human life. Furthermore, designing a transportation system that relies on humans not making mistakes, is not truly a system made for humans.

This proposal focuses on how a specific crash type can be eliminated city wide through a safe systems approach. First, a specific crash type to eliminate will be chosen, along with a local example of this type of crash. This crash will be analyzed thoroughly, with proposals for intersection intervention alternatives. Lastly, a comprehensive plan for eliminating this crash type on the city wide scale will be proposed.

Crash Type

The chosen crash type to analyze for this proposal is right-turn crashes, commonly referred to as "right-hook" crashes. Since 2018, there have been over 10,500 right turn crashes in Denver, with 15 of them being fatal. Although the percentage of fatal right turn crashes is relatively low, at 5%, this turn type disproportionately affects vulnerable road users, specifically bicyclists. Since 2018, 19% of bicyclist fatalities have been the direct result of a right turn crash. Right turn crashes typically occur when a driver:

- Takes a right turn too fast
- Fails to yield/stop
- Fails to check for pedestrians & bicyclists on right side before turning

Historically, most right-turn crashes have been attributed to human error. Whether a driver is speeding, is distracted, or fails to yield/stop, the fault has widely only been placed on the driver. While human error does a play a role in right turn crashes, that is not to say that it is the only cause of these crashes, and much less that this crash type is preventable. Approaching this crash through a systemic approach acknowledges that this crash type is preventable, and that planners and engineers can largely effect these kinds of crashes.

Crash Example

A local example of a fatal right turn bike crash was analyzed for this proposal. The selected crash occurred on July 24,2019 at the Marion Parkway & Bayoud Avenue intersection in the Washington Park neighborhood of Denver. Figure 3 shows the location of the crash.

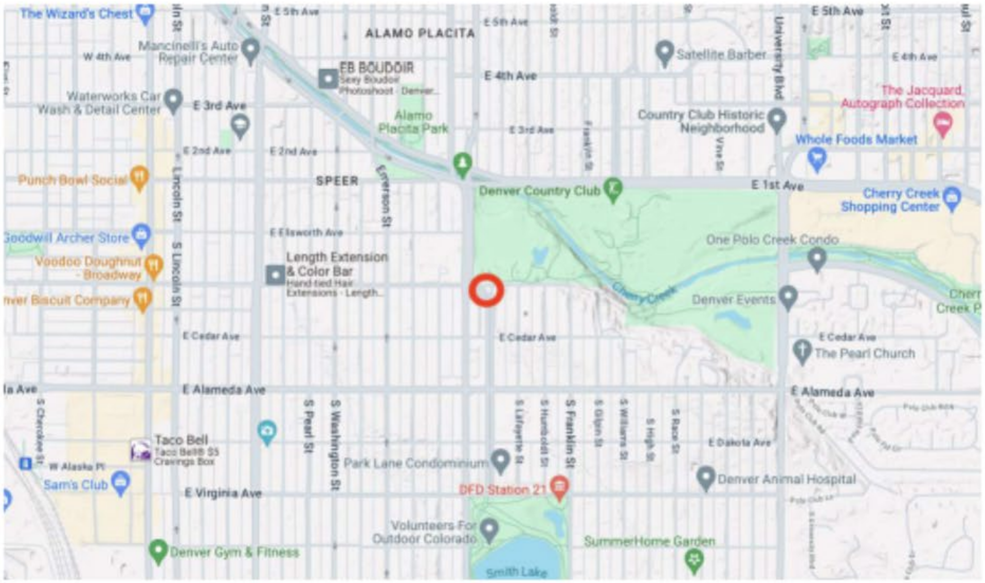


Figure 2: Alexis Bounds Crash Location

The crash occurred when Alexis Bonds was traveling northwest in a designated bicycle lane, when a driver also traveling northwest on Marion Blvd made a sudden right turn onto Bayoud Avenue. Alexis Bounds was struck by a truck and dragged underneath the vehicle after the collision. Figure 2 shows the vehicle paths during the crash from the official police report.

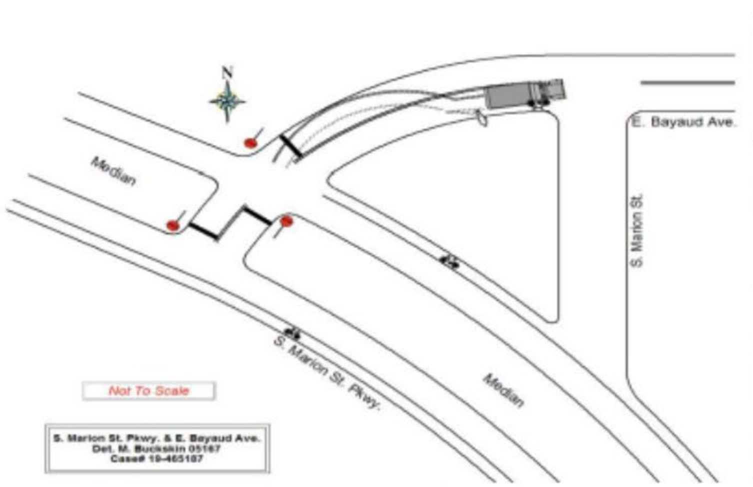


Figure 3: Police Report Crash Diagram

It is important to understand the intersection that this occurred on as well as the surrounding roadway network of the crash location. At the time of the crash, Marion Parkway was a two lane, median separated local collector. This roadway had one lane of traffic , a painted bike lane, and on street parking in each direction. The posted speed limit was 25 mph. Marion Boulevard provides north-south local connectivity from Washington

Park to the Denver Country Club. Bayoud Avenue is a two local street that provides local connections to the immediate surrounding neighborhood. To the east, Bayoud Avenue had a cross section of one travel lane and on street parking in each direction. To the south, Bayoud Avenue serves as a southbound one-way alleyway. Figure 4 shows the cross section of Marion Parkway at the time of the July 25 crash. The view from the northwest-approach at the time is shown in figure 6.

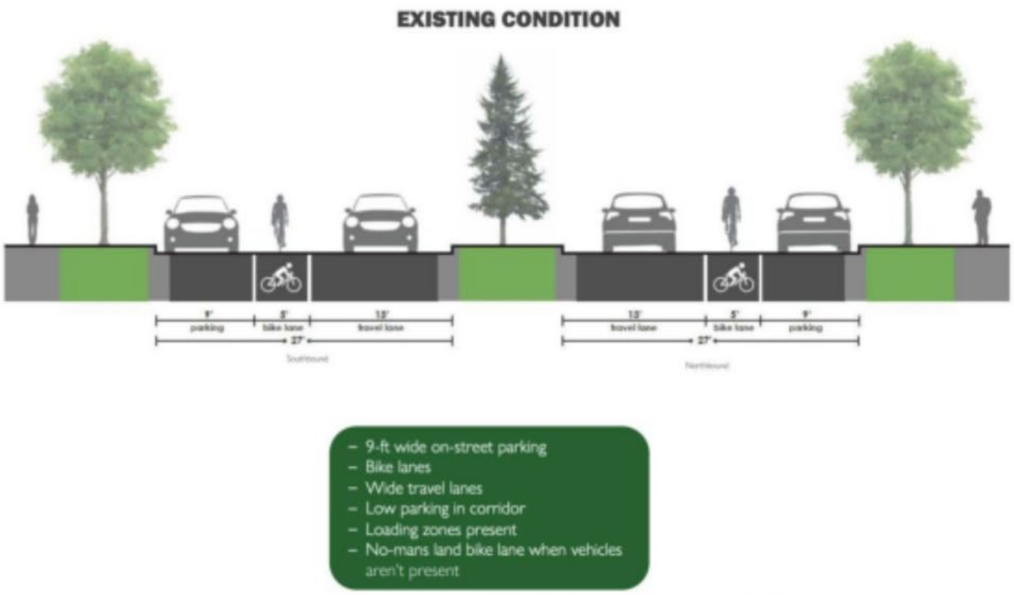


Figure 5: Marion Parkway 2019 Cross Section (DOTI)

Figure 6: 2019 northwest approach.

Per the official crash report from the Denver Police Department, the driver who struck and killed Alexis Bounds was cited with careless driving resulting in death. The contributing factor was deemed to be that the driver was unfamiliar with the area. Historically, this is where the blame officially lands, with the driver. The blame is placed solely on the driver, and it is deemed to be the cause of simple human error. It has also been widely accepted that human error is largely unpredictable, and unpreventable. While human error can surely be unpredictable, a safe systems approach to this type of crash questions who exactly is at fault, at why the crash truly happened. When analyzing this specific fatal crash, the following questions must be asked:

1. Could this crash have been prevented through safer street design?
2. Was the bicycle infrastructure truly protecting Alexis Bounds?
3. Could human error be more forgiving?
4. Was the current street design allowing the careless driving?

While many more questions can be asked, these 4 allow for a deeper dive into the crash. While this crash may usually be deemed to be the sole fault of the driver, and thus unpreventable due to the inevitability if human error, it must not be approached this way to truly achieve vision zero. In this case, whether the infrastructure and design of Marion Parkway was responsible for Alexis Bounds' death must be questioned. Through analyzing Marion Parkway and its intersection with Bayoud Avenue, the following concerns are noted:

1. **Wide Travel Lanes**
   At the time of the crash, the travel lanes on Marion Parkway were 13 feet wide, which is wider than the standard Denver lane width of 12 feet. The wide travel lane width encourages faster vehicle speeds along the roadway.
2. **Bike Lane Placement:**
   Although Marion Parkway had designated bike lanes, which Alexis Bounds was traveling in, these bike lanes have several inadequate design features. Firstly, the placement of the bike lanes does not prioritize bicyclist safety. By placing the bike lane between the travel lane and the on street parking, it leaves the bicyclist exposed to the vehicular traffic as well as a dooring risk. The bike lane in the northwest direction also ends suddenly after Bayoud Avenue. Bicyclists are forced out of a dedicated bike lane and forced to ride with vehicular traffic or onto a sidewalk.
3. Bike Lane Protection
   As mentioned previously, the bike lanes on Marion Parkway offered no buffer on either side of the bike lane. The Bike lanes were also offered no physical protection in the form of a curb, planters, a landscaped buffer, or a painted buffer.

These design features indicate that bicyclists were not prioritized on this roadway. Instead, it is very clear that the movement and parking of vehicles was prioritized on this roadway over the safety of bicyclists. A safer roadway design may have been able to safe Alexis Bounds' life on July 24, 2019.

Proposed Intersection Improvements

The following section outlines proposed improvements for the Marion Parkway and Bayoud Avenue Intersection, as well as Improvements for the roadways themselves. These improvements are meant to resemble an ideal improvement scenario, where budget and other limiting factors are not considered. The following improvements are recommended reduce right hook crashes as well as improve overall traffic safety at this intersection:

1. **Reconfigure Marion Parkway**
   Given the City of Denver's recognition to make Marion Parkway a high comfort bike facility, the overall cross section is recommended to be redesigned to improve safety. The first recommendation is to rearrange the travel lanes and their dimensions. It is recommended to change the travel lane to 10 feet in each direction in order to encourage slower driving speeds. The parking lane is to be placed adjacent to the travel lane at a width of 8 feet. A one-way protected bike lane with a width of 6 feet is also recommended. The Protection can vary, it is essential to provide a physical barrier between the parking lane and the bike lane. This can be done through a tall curb, movable planters, or bollards. The proposed improvements for Marion Parkway are shown in figure 7.

Figure 7: Marion Parkway Proposed Improvements

2. **Reconfigure Bayoud Avenue.**
   It is recommended that the cross section Bayoud Avenue be reconfigured east of Marion Parkway. Given that the eastern leg of Bayoud Avenue has a traditional cross section and provides. Given the existing 45 foot cross section with two travel lanes and a parking lane on each side, the following changes are recommended: Given the very few occupied parking spots along this street, it is recommended to remove the

parking lanes entirely in order to install protected bike lanes. Given that this is a lower speed roadway, the protection recommendations are not as intense as on Marion Parkway. It is recommended to have install a protected bike lane in each direction, with protection being offered via a minimum of 2 a foot wide physical barrier, such as a landscaped buffer or a curb. The proposed Bayoud Avenue improvements are shown in Figure 8.

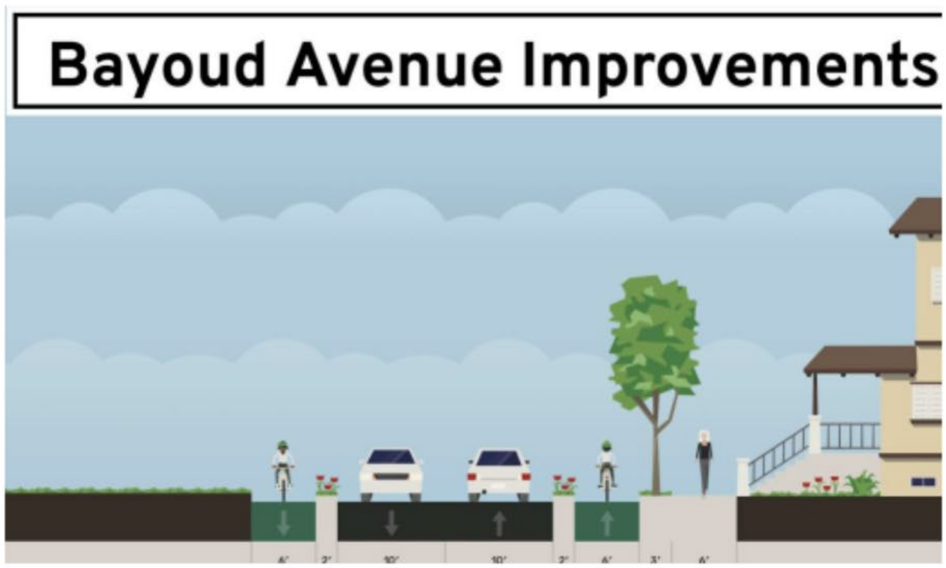


Figure 8: Bayoud Avenue Proposed Improvements

3. Intersection improvements
   Although the Improvements recommended to both Marion Parkway and Bayoud Avenue are important, given hat the crash pictured directly at the intersection, the most important improvements should occur at the intersection itself. The following improvements are recommended:
   a. **Convert Southbound Bayoud Avenue into one-way traffic**. Given that vehicles traveling northwest on Marion Pkwy hoping to get onto Bayoud Avenue will most likely use Marion St, the right turn movement involved in this crash is an unnecessary movement. Vehicles hoping to access Bayoud Avenue from Marion Pkwy can access it via Cedar Ave to the South
   b. Tighten Turn Radii. The right turn radius can be reduced by narrowing the travel lanes and extending the curbs. In this case, this can be done by extending the bike lane protection. Reducing the turn radius forces drivers to approach the turn at a much slower speed. A tighter turn radius also allows vehicles to be perpendicular to bikes and pedestrians during the turn, allowing for better visibility.
   c. Install diverter to prohibit vehicular traffic through median. As minimal traffic is expected for movements through the median, it is recommended to close

this off to vehicles. Bollards or other protective barriers should be installed to clearly indicate the closed area. This area should remain open for bikes and pedestrians.

d. **Install painted pedestrian and bike crossings.** White painted crosswalks should be installed at pedestrian crossing points, as well as green painted bike crossing as the bike lanes cross the intersection. This allows for better visibility and predictability for pedestrians and bicyclists.

Figure 9 illustrates the proposed alignment improvements for the Marion Parkway & Bayoud Avenue intersection.

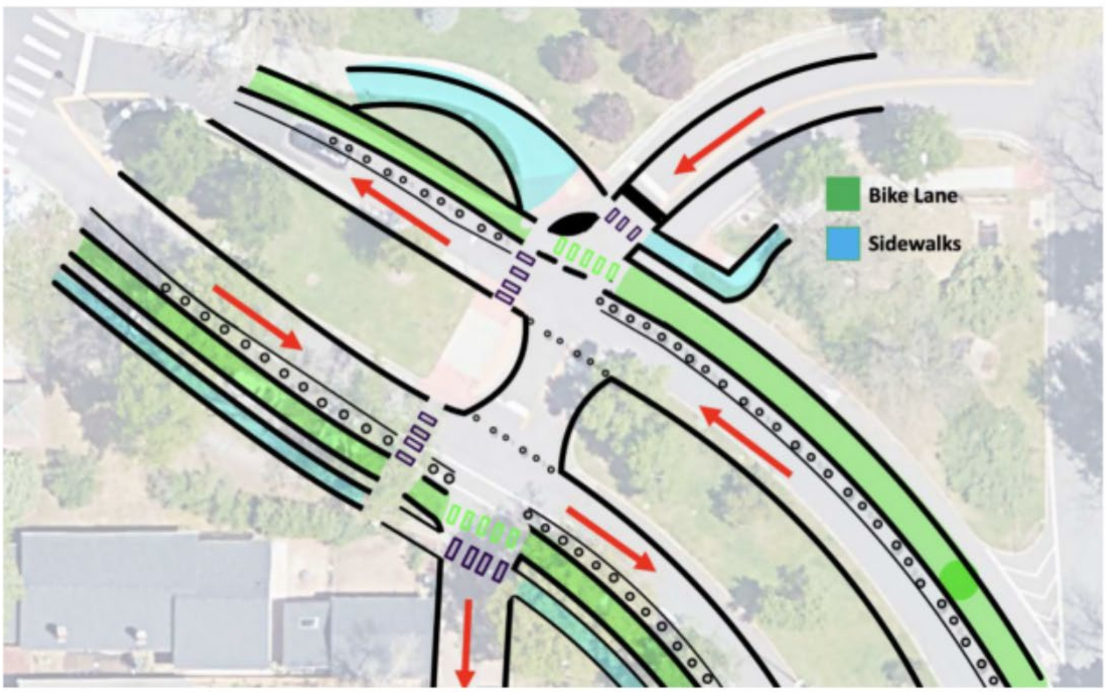


Figure 9: Proposed Intersection Improvements

As previously mentioned, the proposed improvements in this scenario represent those for an ideal scenario where budget is not a consideration. The improvements mentioned above are the ideal improvements for improving safety at this intersection.

City-Wide Recommendations

As mentioned above, the proposed recommendations for the Marion Parkway & Bayoud Avenue intersection are ideal for improving safety at that particular intersection. However, those improvements would require significant changes to the existing hardscape, as well as significant additions for the protected bike facilities. Thus, those improvements would not be feasible at the city-wide scale.

Intervention alternatives at the city-wide scale requires a much more complicated approach, as budget, time, and other factors apply. The proposal recommends several improvements that can be made at the ctiy-wide scale within the $100 million budget. These recommendations can largely be categorized into these two categories:

1. **Policy Changes**: Policy change improvements are those that may not directly change the design of any intersections. These policy improvements are meant to. Build upon design changes to either make design changes permeant through policy, aid design changes through a policy, or add improvements that can not be done through design changes. An example of a policy is requiring all vehicles to yield for pedestrians at crosswalks
2. **Design Changes**: Design changes will be the most direct and impactful form of improvements. Design changes will be physical improvements made directly to roadways and intersections.

While most of the recommendations can be separated into being either policy or design changes, several recommendations work together. With the systemic approach, all city-wide recommendations aim to land withing these four essential concepts:

1. **Forgiveness**: The safe systems approach does acknowledge the role of human error in crashes. However, through safe design and policy, human error does not need to always end in the loss of life. Safe infrastructure should allow for the consequences of small human error to be minimalized at all times.
2. **Predictability & Simplicity**: Is every intersection is given different safety measures, and if design standards are inconsistent throughout a city, it will lead to confusion amongst all road users. Thus, safety measures should aim to be as effective as possible while also being as simple as possible. Keeping this consistent will allow for better predictability throughout a streets users.
3. **Limiting speeds**: Ensuring that vehicles are forced to drive slower Is essential to roadway safety. Given the speeding effects on fatality rates, reducing speeds should be an essential part of any design improvements.
4. **User Separation**: Separating road users allow for higher comfort for all road users. This also limits the dangerous conflicts between vehicles and other users.

Design Recommendations:

1. **Tighten Turn Radius**. Tightening turn radii is essential to reducing vehicle speeds as a right turn is made. This will also allow for better visibility of Pedestrians and Bicyclists crossing on the right as a tighter turn radius forces vehicles to be more perpendicular to the crossings. This can easily be achieved with flex posts and

paint as a cost effective solution. An ideal solution would include extending the physical curb or installing bollards.

2. **Eliminate/ repurpose right turn slip lanes**. Right turn slip lanes are channelized turns that allow for vehicles to take a right turn at a high rate of speed. The goal of slip lanes is to be able to move as much vehicles through a right turn as possible. Slip lanes create a very hostile environment for pedestrians & bicyclist, as drivers often approach these turns t a very high rate of speed, with minimal yielding at designated cross walks. Eliminating these & repurposing them as sidewalks, bike boxes, or bike lanes will improve the overall safety of that intersection.
3. **Install Pedestrian only phases and Leading Pedestrian Intervals**. Installing pedestrian only phases at signalized intersections will allow for pedestrians to cross the intersection without any vehicle conflicts. Leading pedestrian intervals allow for pedestrians & bicyclists to begin crossing before vehicles. These two improvements minimize the amount of time that a pedestrian or bicyclist is exposed to drivers turning right.
4. **Install painted crossing for all pedestrian and bike crossings.** This improvement entails in ensuring that every pedestrian and bike crossing is painted. Pedestrian crossing should be painted white, and bike crossing should be painted green. This will ensure comfort for users crossing as the painted crossing give pedestrians and bikes a designated area to cross. This also allows drivers to more easily predict pedestrian and bicyclist activity.

Figures 10 & 11: Design Improvement Examples

Policy Recommendations:

1. **Install red light/stop cameras at intersections.** Installing cameras and fining drivers who do not fully stop at a stop sign or drivers who turn on red would improve the safety by reducing the amount of drivers who illegally turn right. This will ensure

that drivers stop and approach right turns slowly. The money made from these violations can be used to further fund these improvements. These should first be placed at the most dangerous intersections in the city, or those with the lowest stop/yield rates.

2. **Update city zoning codes to allow for more mixed use developments.** Upzoning will allow for more dense, walkable areas. Areas that are dense in population also tend to have improved roadway safety. This is due to the decreased number of car trips, and increased walking, biking, and transit trips. Although his is not a transportation specific policy, the effects of upzoning a city will have positive benefits on the transportation systems surrounding them.

Figures 12 & 13: Policy Change Examples

Design + Policy Improvements:

1. **Ban right Turns on Red.** This improvement would initially be implemented as a city-wide policy. Vehicles would no longer be allowed to make a right turn while the signal light is red at any signalized intersection. Given that most right hook crashes involving a pedestrian/bicyclist involves a driver turning right while only looking at oncoming traffic to the left, this would nearly eliminate that type of crash. Design features that would compliment this policy would be to redesign stop bars at signalized intersections. Since RTOR will be prohibited, the stop locations for vehicles can be pushed further back. This will not only discourage drivers from illegally making the right turn, but it will also allow pedestrians and bicyclists to be more visible to drivers. This design change would only require the old paint to be removed and a new stop bar to be painted.
2. **Daylighting Intersections.** The policy improvement associated with this would be to prohibit parking within 30-50 ft at any given intersection, where on street parking exists. This would allow for better visibility as users approach the intersection. This would better allow drivers to see peds/bikes crossing before they turn right, as opposed to potentially not seeing anybody due to parked cars or other obstructions. To further ensure this, a curb extension design feature can be implemented. Ideally, the existing curb is extended, but this can also be done with flex posts and paint.

3. **Update Design Standards.** An important recommendation is to update the cities design standards. Firstly, the city must adapt city bikeway and safe streets guidelines into city-wide standards. This will allow for safer street design whenever a new street is built, changed, or improved. This will allow for safer streets at their conception, rather than applying safety features years later, typically after several crashes or fatalities. Furthermore, this would allow for a key aspect of systemic safety, simplicity and predictability. Making a city-wide standard for how all bike lanes, pedestrian crossings, and normal streets look, feel, and operate allows for all users to better predict each others decisions and movements.

Figures 14 & 15: Deisgn+Policy Improvement Examples

Cost Estimate Analysis

As mentioned previously, ideal intersection improvements are not feasible at a city-wide scale, partly due to budget constraints. The recommendations in this proposal aim to be within the $100 million budget granted by the Marshall Foundation. The budget analysis will be broken up into the same sections as the city-wide improvement recommendations.

Design Improvements:

1. **Tighten Turn Radius**: Given the material and labor costs to use flex posts and paint, this would cost around $2,000 per intersection. Applying this to 4000 intersections would cost **$20 million**
2. **Eliminate/ repurpose right turn slip lanes**. : Given the material and labor costs to use flex posts and paint, this would cost around $1,000 per intersection. Applying this to 100 intersections would cost **$100,000**
3. **Install Pedestrian only phases and Leading Pedestrian Intervals**: Signal phasing changing efforts cost an estimated $2000 per intersection. Applying this to 2000 intersections would cost **$10 million**
4. **Install painted crossing for all pedestrian and bike crossings.** This would be a relatively cheap improvement, as only paint is needed. The estimated cost is $500 per intersection, or **$5 million** for 10,000 intersections

Total= $35,100,000

Policy Improvements:

1. Install red light/stop cameras at intersections: The average cost for the installation of red light cameras at an intersection is $100,000. If these are installed at 200 intersection across the city, the total cost would amount to **$20 million.**
2. **Update city zoning codes to allow for more mixed use developments:** While this improvement seems like it would essentially be free, administrative, legal, and public engagement efforts would still cost the city money. It is estimated that this would cost the city around **$5 million.**

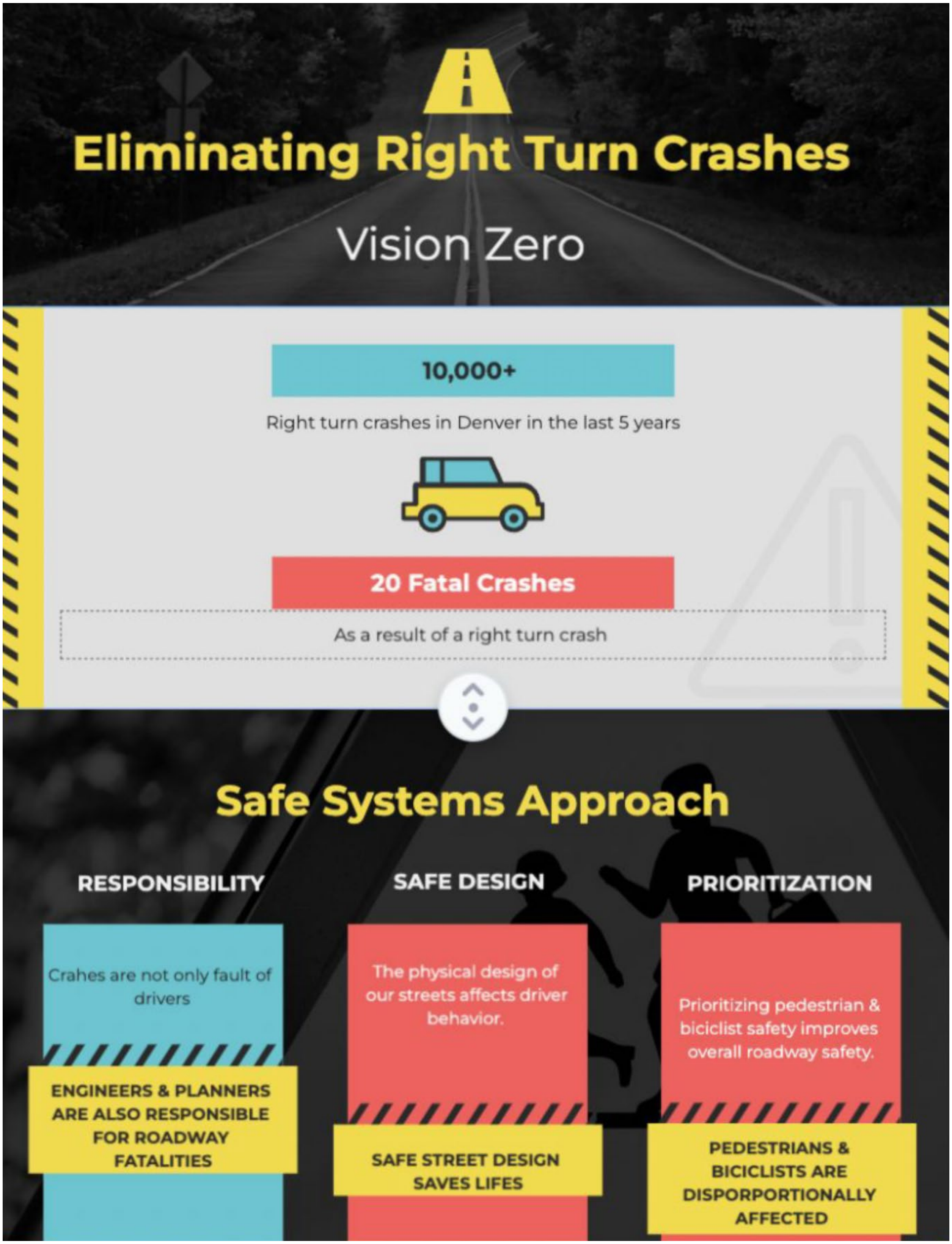
Total**=$25 million**

Design + Policy Improvements:

1. Ban right Turns on Red. This effort would require costs for the policy application and the stop bar relocation, which will only require paint. This is estimated to cost $1000 per intersection, or **$3.5 million** for Denver's 3500 signalized intersections.
2. Daylighting Intersections. This effort would require costs for the policy application and the flex post & paint for material costs, which will only require paint. This is estimated to cost $2000 per intersection, or **$20 million** for 4000 intersections.
3. Update Design Standards. This improvement would only consist of labor and administrative costs, with an estimated cost of $1 million.

Total=**$24.5 million**

The total estimate is around $85 million. The remaining $15 million should be used at specifically dangerous intersections, where more permanent safety improvement should be made aside from using flex posts and paint.


Eliminating Right Turn Crashes
Vision Zero
10,000+
Right turn crashes in Denver in the last 5 years
20 Fatal Crashes
As a result of a right turn crash
Safe Systems Approach
RESPONSIBILITY
SAFE DESIGN
PRIORITIZATION
Crahes are not only fault of drivers
ENGINEERS & PLANNERS ARE ALSO RESPONSIBLE FOR ROADWAY FATALITIES
The physical design of our streets affects driver behavior.
SAFE STREET DESIGN SAVES LIFES
Prioritizing pedestrian & biciclist safety improves overall roadway safety.
PEDESTRIANS & BICICLISTS ARE DISPORPORTIONALLY AFFECTED

Design improvements consist of 60% of the total estimated cost
60%
Design Vs Policy
$100 Million Budget
$85 Million Estimated Cost
Cost Effective Solutions:
Flex Posts
Paint
Policy Changes
Design
· Tighter Turn Radius
· Recessed Stop Bars
· Curb Extensions
· Pedestrian Phases
Policy
· Ban Right Turns on Red
· Install Red Light Cameras at All signals
· Build More Mixed Use Developemnts