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Road Safety Evidence Review

Engineering Countermeasures for Left Turns at Signalised Intersections: A Review

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Key Findings

- Left turn crashes may take place at high speeds and at specific angles;
- Various countermeasures for left turns have been designed and evaluated;
- Protected left turns, roundabouts, and warning systems can be effective in increasing left-turn safety.

Abstract

Left turn crashes can impact the safety of the drivers due to the speed and angle at which they occur. Left turns are specifically reported to affect older drivers more than the other types of crashes. This paper provides a review of the existing engineering countermeasures that have been evaluated to improve driver safety at left turns. Twenty-eight studies on left turn signal displays (protected left turns, flashing yellow arrow, and digital countdown timers), intersection geometry (offset left turn lanes, diverging diamond interchange, roundabouts, exit lanes for left turn, left turn bay extension, and contraflow left turn lanes), and driver warning systems (infrastructure warning systems, and in-vehicle warning systems) are reviewed. Eighteen studies were evaluated in the field, nine in laboratory environments, and one online. All countermeasures demonstrated varying levels of effectiveness. We found protected left turns, roundabouts, and warning systems to be the most effective engineering countermeasures. Advantages and disadvantages of each countermeasure and research shortcomings of the evaluation studies are discussed. Review findings may help practitioners and researchers guide more effective countermeasures for left turns for older drivers.

Keywords

left turns, signalised intersections, countermeasures, protected left turns, flashing yellow arrow.

Introduction

Left turn crashes can affect traffic safety, especially since they can happen at higher speeds and the impact direction and angle can cause serious injuries and fatalities. According to the National Collision Database (NCDB) of Canada, since 1999, 466,601 people have been involved in left turn crashes, which have resulted in 239,103 injuries and 1,590 fatalities. 237,192 of these cases happened at fully operational traffic signals, 4,202 when traffic signals were in the flashing mode, 147 in reduced speed zones, 47,804 at the stop signs, 2,698 at the yield signs, 707 at the pedestrian crossings, 13 at school crossings, 125 in presence of warning signs, 209 where there was a no passing zone sign, 260 in areas with markings on the road (e.g., no passing), 95 at railway crossing with signals or signs, 15 in presence of police officer, 335 in presence of school guards, and 151,299 where no form of traffic control (such as a crosswalks or pedestrian yield signs) was present. Only in 2016, 22,158 crashes happened at left turns in Canada, injuring 11,253 people and leading to 60 fatalities. As per the US National Highway Traffic Safety

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Association (NHTSA), left-turn conflicts constitute 22.2% of all crashes in the United States (Chen & NHTSA, 2010).

Drivers turning left at signalised traffic intersections may be prone to risks of violations and crashes, depending on several factors such as driver behaviour, age, intersection geometry, type of left turns, and pedestrian crossing (Li et al., 2016). Older drivers' crash involvement is higher at intersections, especially signalised four-way intersections requiring left turns, partly due to their failure to yield the right of way to opposing traffic (Braitman et al., 2007). Not only are intersections particularly risky road sections for older drivers, but they are also the most frequent category of crash in which older drivers are involved (Guerrier et al., 1999).

Left turns at intersections can specifically pose a threat for older drivers. A study has shown that drivers at the ages of 65 to 69 are 2.26 times more at risk for multi-vehicle crashes at intersections, which is higher than the other situations, where the risk is 1.29 higher. Also, for drivers at the ages of 85 and higher, this number increases to 10.62 times, as compared to the risk of 3.74 at other situations (Preusser et al., 1998). Research in the field (Bao & Boyle, 2009) and on a driving simulator (Romoser & Fisher, 2009; Romoser et al., 2013; Schneider et al., 2019) further indicates that older drivers are less likely to glance for threat vehicles as they approach and navigate intersections. Typically, and alarmingly, older drivers in the field take a glance to check the absence of threat vehicles to the direction opposite of their intended path only at about 40 percent of the intersections (Romoser & Fisher, 2009). During left-turn operations, diminishing ability to divide attention to their immediate front and a location of imminent, and often latent, threat and to turn the steering wheel sharply enough can compromise the ability of aging drivers (Brewer et al., 2014).

A number of explanations have been proposed for why older drivers are more prone to crashes while manoeuvring left at intersections, including age-related declines in the ability to multi-task (Clapp et al., 2011), in working memory capacity (Zacks et al., 2000), in distractibility (Kramer et al., 1999), in the attentional field of view (Ball, 1990), in decision making (Braitman et al., 2007), in vision (Owsley et al., 1991), and in flexibility (Eby, 1998). These declines in cognitive, sensory and physical faculties can confluence and impact safe driving behaviour for older drivers, particularly at intersections (McKnight & McKnight, 1999).

This paper not only provides a review of the literature on countermeasures that were designed and evaluated to reduce risks of left-turn crashes but also seeks to highlight that while such measures have been broadly evaluated across regions, little work has focused on the explicit effectiveness of these measures for older drivers – the population group most vulnerable to crashes while turning left at intersections (only 5 out of the 18 studies reviewed here evaluated the treatments for older drivers). Such countermeasures may be broadly categorised into three main types: Engineering, Enforcement and Education. The Engineering countermeasures may be further grouped into three categories, namely, Left Turn Signal Displays, Intersection Geometry and Driver Alerts.

In the following sections, we discuss the scope of our study and our inclusion/exclusion criteria in greater detail, followed by a review of the literature on existing left-turn countermeasures. Advantages and limitations of each countermeasure are discussed, and research shortcomings are indicated. We conclude by discussing areas of potential advancements towards increasing intersection safety by improving the effectiveness of left-turn countermeasures for drivers.

Methodology

The current paper presents a systematic review of countermeasures that may improve driver behaviour as it relates to safety while navigating left turns at signalised intersections. The purpose of this literature review is to - 1) identify the most effective engineering countermeasures that can improve driver behaviour at left turns, 2) note gaps and limitations in previous research, and 3) suggest alternatives towards improving existing countermeasures.

Several inclusion and exclusion criteria were employed in the current review. Articles were only included in the review if they - 1) present experimental evidence in the form of human subjects data regarding the effectiveness of a countermeasure at improving driver behaviour, 2) focus on engineering countermeasures, 3) target signalised intersections, 4) are retrievable online, 5) focus on safety-based measures, and 6) are written in English. Articles were excluded if they 1) studied education and enforcement countermeasures, or 2) present scientifically inconclusive evidence (such as small sample sizes or no significant measure).

An intensive search was conducted until July 2021 to identify applicable peer-reviewed publications. Ten databases and electronic indexed archives were included in this search – TRID (Transportation Research International Documentation), CiteSeer, SAGE, PubMed, Scopus, Refworks, Web of Science, Mendeley, EBSCO Host and DataCite. A "snowballing" strategy (identify references cited in initially identified papers) was applied to uncover additional articles that met the scope of the review. The key words and phrases used for this literature review included - "left turn safety measures"; "left turn engineering countermeasures"; "gap acceptance mitigation"; "left turn signal displays"; "flashing yellow arrow"; "protected permissive left turns"; "heads up displays left turns"; "offset left turn lanes safety"; "diverging diamond interchange safety"; "pavement markings for left turn safety"; "warning systems left turn safety"; "vehicular signal countdown timer''; "operational efficiency''; "traffic safety''; "left turn bay extension''; "exit lanes for left turn''; "left turn infrastructure warning systems"; "in-vehicle warning systems"; and "filter turns".

Following quality assessment, our search yielded 28 articles. Among the 28 studies, 18 studies were conducted in the field while 9 studies were completed on a driving simulator and 1 study was administered online. 20 studies reported success in the evaluation of safety measures while 8 studies presented contrasting evidence. 2 studies involved older adults (both assessing driver warning systems), and 3 had participants with a wide age range, including older adults (1 study each on protected left-turns, driver warning systems, and offset left-turn lanes).

Scope of Review

The implementation of appropriate engineering, enforcement or education countermeasures can improve driver behaviour while navigating left at signalised intersections and lower drivers' crash risk. Literature documents the existence of several such countermeasures (Romoser & Fisher, 2009; Brehmer, 2003; Hummer et al., 2016; Knodler et al., 2005). However, not all countermeasures are found equally effective. Some measures present advantages in certain situations while other measures raise more confusion than bring forth safety. Left turn conflicts are overrepresented among older driver fatalities and therefore, it is imperative to conduct and document a detailed literature review that broadly examines a range of countermeasures that improve left turn safety, scopes the advantages and disadvantages of each measure, identifies gaps in existing research on left turns, and suggests future research to further improve the effectiveness of countermeasures.

While there are effective enforcement and education countermeasures in literature, this review solely focuses on engineering countermeasures that have been systematically studied. The current review specifically focuses on engineering countermeasures for three reasons – a) engineering measures have been more broadly and widely evaluated, b) engineering countermeasures are also more easily implementable and c) non-engineering measures are relatively fewer in number. The engineering countermeasures reviewed here can be broadly classified into three categories - left turn signal displays (protected left turns, flashing yellow arrow, and digital countdown timers), intersection geometry (offset left turn lanes, diverging diamond interchanges, roundabouts, exit lanes for left turn, left turn bay extension, and contraflow left turn lanes) and driver warning systems (infrastructure and in-vehicle warning systems). The following section captures the essence of the research findings across the countermeasures.

Engineering Countermeasures

This section reviews a variety of engineering countermeasures to assess their effectiveness in increasing left-turn safety. Left turn signal displays (see Figure 1; protected left turns and flashing yellow arrow), intersection geometry-based measures (offset left turn lanes, diverging diamond interchange, and roundabouts) and driver alerts (driver warning systems) are reviewed. Tables 1-3 summarise the results with respect to (w.r.t.) different countermeasures (C-measure) and are discussed in subsequent sections below.

Left Turn Signal Displays

Information provided to drivers on traffic signals can be crucial for intersection safety. Signal displays are used as safety measures to mitigate left-turn crashes and violations, and to control intersection efficiency. The suitable research studies related have been summarised in Table 1.

Protected Left Turns

At some signalised intersections, an exclusive left-turn signal is utilised to allow the left-turning drivers to pass safely through the intersection. These are known as Protected Left Turns (PLT), as left-turning drivers are "protected" from the opposing traffic in the intersection while they are making left-turns. A PLT signal is usually

Figure 1: Examples of Left Turn Signal Displays

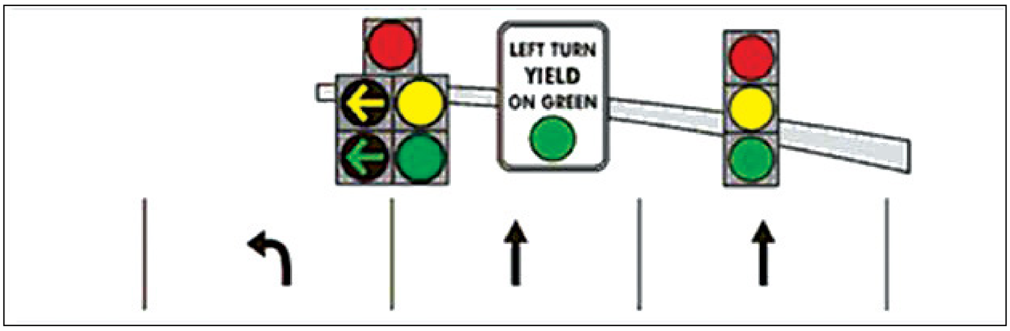

Figure 2: Five-Section Permissive-Protected Left Turn Display
(From https://www.fhwa.dot.gov/publications/research/safety/04091/04.cfm)

in the form of a green arrow pointing left to indicate that drivers may pass safely through the intersection. For the duration of a PLT phase, drivers going straight on adjacent lanes and the opposite traffic will typically see a red light. Therefore, this countermeasure aims to protect left-turning drivers from intersection conflicts (Agent et al., 1995).

A field experiment in New York City (Chen et al., 2015) compared 68 signalised intersections before and after implementing PLT phasing. Left-turn crashes were reduced by 77% when PLT was in place, with a 56% reduction in total crashes. This was also observed in another field-based study in Kentucky (Stamatiadis et al., 1997), where 408 vehicle approaches at 217 intersections were investigated to compare the performance of Protected and Permissive left-turn phases. Permissive left turns (also referred to as filter turns (Akcelik, 1989)) allow drivers to turn left only after yielding to conflicting traffic, and generally do not have a dedicated left-turn signal. The study concluded that in presence of a PLT phase, the average left-turn crashes per year per approach was 0.20 crashes, compared to 0.50 crashes when the setup was changed to a Permissive Left Turn phase. Both of these studies favour the positive effectiveness of PLT in improving left-turn safety.

Another computer-based driver survey evaluated 2,456 drivers on their understanding pertaining to PLT. A total of 73,950 survey responses were received across 200 scenarios — 24,683 related to PLT indications (Noyce & Kacir, 2002). Findings from the study demonstrated that driver understanding is reduced and driver error is significantly increased from the simultaneous illumination of the green arrow and the red ball in a five section permissive-protected left turn display (see Figure 2) during a protected left turn phase. Drivers over the age of 65 also showed the same pattern of behaviours.

Flashing Yellow Arrow

In contrast to PLT, permissive left turn situations allow drivers to turn left only after yielding to conflicting traffic. However, a prime concern with Protected/Permissive Left Turn (PPLT) signals is the “yellow trap”, where drivers face a dilemma while turning left during signal transition. To combat this issue, a Flashing Yellow Arrow (FYA) system has been developed to improve traffic safety and is regarded as the most effective among other forms of permissive indications, such as flashing circular yellow, flashing circular red and circular green (Brehmer, 2003;

Knodler et al., 2005). An FYA signal is typically placed in conjunction with standard red, green, and yellow traffic lights as shown in Figure 1. It informs drivers (see Figure 1) to make a left turn only after yielding to the oncoming traffic (Radwan et al., 2013).

A study on PPLT (Knodler et al., 2005) conducted using a simulator indicated positive effectiveness of FYA implementation. 48 participants were asked to drive through a continuous loop of 14 intersections, where 8 of the scenarios had left turns. No statistically significant differences were obtained between the FYA and non-FYA tests. On average, drivers seemed to behave in the same manner throughout the two tests, in terms of making correct left turns.

A field-study (Simpson & Troy, 2015) developed and analysed crash modification factors for the implementation of FYA. A before-and-after crash analysis was performed on 13 intersections. Crash data were collected from before FYA implementation (permissive-only circular green) and after FYA implementation (protected/permissive). After replacing standard circular green with FYA, a statistically significant decrease in left-turn crashes by up to 40% and a 35% reduction in injury crashes were observed. A similar before-and-after field study (Pulugurtha et al., 2011) conducted in North Carolina evaluated the effectiveness of FYA at 6 signalised intersections during the period 2007-2008. Five out of the six intersections showed promising outcomes in terms of crash mitigation, while one of them actually experienced a slight increase in crashes upon installing FYA.

Digital Countdown Timers

Digital countdown timers (DCT) show the time remaining in the current signal phase, mainly in seconds. DCT are typically of three types: green signal countdown timer (GSCT), red signal countdown timer (RSCT), and continuous countdown timer (CCT). Each DCT type has

Table 1. Summary of Contributions w.r.t. Left- Turn Signal Displays.

Type	Lit.	Study	Sample Size	S.	Post-Implementation Results
Protected Left Turn	Chen et al., (2015)	Field	68 intersections	Y	↓ Left-turn crashes by 77% ↓ Total crashes by 56%
	Stamatiadis et al., (1997)	Field	217 intersections; 408 approaches	Y	↓ Avg. crashes per year per approach from 0.5 with Permissive to 0.2 with Protected
	Noyce & Kacir (2002)	Online	2456 drivers; 24683 responses	N	↓ Driver understanding ↑ Driver error
Flashing Yellow Arrow (FYA)	Knodler et al. (2005)	Lab	48 participants; 14 intersections with 8 left-turns	N	No difference between FYA & non-FYA
	Pulugrutha et al. (2011)	Field	6 intersections	Y	↓ Avg. crashes per year at 5 intersections [8.7→8, 28.3→22, 15.3→9, 19→10, 18→11] ↑ Avg. crashes per year at 1 intersection [33.3→37]
	Simpson & Troy (2015)	Field	13 intersections	Y	↓ Left-turn crashes by up to 40% ↓ injury crashes by 35%
Digital Countdown Timers (DCT)	Chiou & Chang (2010)	Field	2 intersections; 6 participants	Y	↓ Significant red-light violation Crash rate: NA ↑ Crossing of stop line

(S. stands for Success (Effectiveness of the Countermeasure); Lit. Stands for Literature; Y: Yes; N: No.)

been found to have varying impacts on the intersection safety (Fu et al., 2015). Chiou & Chang (2010) studied the impact of DCT on driver response during left-turns and found that DCTs may significantly reduce the vehicle's stop time at the ending of green signal phase. The study also found that the presence of DCTs extended the dilemma zone by 28 meters which may potentially lead to an increase in rear end crashes.

Intersection Geometry

Drivers' comprehension of traffic and general intersection safety may also depend on how roads and lanes are designed. Key geometry-based measures in place to improve left-turn safety are reviewed and discussed below (see Figure 3 for examples). The suitable research studies related to this countermeasure have been summarised in Table 2.

Offset Left Turn Lanes

Offset lanes are designed at signalised intersections to provide improved visibility of opposing lanes to left-turning drivers, and to reduce crashes and conflicts due to left turns. This is especially applicable at common intersections, where two opposing left-lanes are directly aligned across from each other, thus obstructing drivers' view of oncoming traffic. An offset is an intentional allowance of a lateral distance between the left edge of a left-turn lane and the right edge of the opposing left-turn lane. A negative offset is when the right edge of the opposing left-turn lane is to the left of the left edge of the primary left-turn lane and vice versa (McCoy et al., 1992).

A naturalistic driving study (Hutton et al., 2015) evaluated the effectiveness of negative and positive offsets on drivers' gap acceptance behaviour by making observations of over 1,000 left-turn manoeuvres at 44 pairs of opposing left-

Figure 3: Examples of Intersection Geometry Measures (left to right): Diverging Diamond Interchange (Adapted from Anderson et al., (2012) Offset Left Turn Lanes (Adapted from Creative Commons CC-BY-SA-2.5)

turn lanes at 33 signalised intersections. Gap acceptance is defined as the minimum space and time between two vehicles that a driver needs to evaluate and accept in order to decide whether to safely enter an intersection or not (Gattis & Low, 1999). Results showed that negative offset left-turn lanes led to significantly longer gap acceptance than positive ones, as the former causes the sight of left-turning drivers to be obstructed by opposing turners 85% of the time, compared to less than 10% of the time at positive offset left-turn lanes. McCoy et al. (1992) alludes to this inference in an observation-based study that determines the necessary offset parameters between opposing left-turn lanes at intersections. Their research supported the design of positive offsets, concluding that negative offset left turns may fail to provide drivers clear and sufficient sight distances for opposing left-turn vehicles.

Further research on this subject was conducted by Tarawneh & McCoy (1997) in a field observation of older-driver performance of 100 test participants, where position of vehicles and time to make left-turn manoeuvres were collected. Across 4 study sites, left-turn lanes consisted of 2 negative, one positive and one zero offsets. The positive offset site yielded the lowest mean left-turn maneuver time than the others; 5.3 seconds for the positive offset, 6.1 seconds for zero offset, and 6.0 and 6.2 seconds for the two negative offsets. Shorter manoeuvre times may equate to longer available sight distances, in which case, positive offsets (Figure 4) may improve left-turn safety. Future research should explore crash-based evidence to further support the assertion.

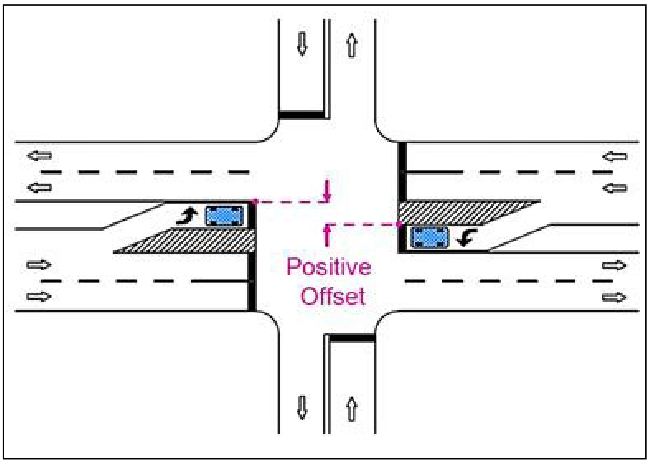

Figure 4: Representation of Positive Offset (Adapted from Bremer et al., 2019)

Diverging Diamond Interchange

An effective intersection-geometry based left-turn countermeasure that was recently designed and implemented is a Diverging Diamond Interchange (DDI). DDI has been gaining popularity among interchange and intersection designs and has proven to carry relatively low infrastructure costs, positive safety assessment results, and high operational benefits (Bared et al., 2005; Edra et al., 2005). A typical DDI layout involves a freeway-crossroad connection made by two on-ramps, along with two off-ramps that consist of a right-turn lane and two left-turn lanes (See Figure 3). The right-turn lane and one of the left-turn lanes led to an on-ramp (Bared et al., 2005).

A before-and-after evaluation conducted in Missouri (Claros et al., 2015) on 6 interchange sites demonstrated that a DDI decreased the total frequency of crashes by 47.9%. Fatal and injury crashes at ramps were 34.3% in the absence of a DDI; post-implementation of the countermeasure, however, eliminated the chances of these crashes. The study also notes a potential concern for wrong-way crashes at DDI, although fatal and injury crashes of this type were only 4.8%. A similar field study (Hummer et al., 2016) extensively observed 7 sites that were converted from a traditional diamond interchange to a DDI. The team analysed about 29 and 19 years of pre- and post-DDI data, respectively, with substantially large overall sample sizes of more than 3,000 crashes. Crashes at all sites reduced by 29%, with an angle-crash reduction of 67%, providing strong evidence of DDI's effectiveness at improving left-turn safety. Angled crashes can include left-turn and right-turn crashes making left turn crashes a subset of angle crashes.

Roundabouts

Replacing intersections with roundabouts can be considered as another approach to reduce crashes due to left turns, especially when there is a high volume of left-turn movements (Tracz & Chodur, 2012). To study the safety effect of roundabouts, Jensen (2013) conducted an observational study, comparing the number of crashes in a period after conversions of intersections to roundabouts (1 to 5 years at different sites) with the expected number of crashes for the same duration, estimated based on the number of crashes before the conversion (period of 5 years). Conversion to roundabouts decreased fatal crashes (62%) and those that led to property damages (24%), both excluding bicycle crashes. A decrease in fatalities, severe injuries, and slight injuries (87%, 58%, and 59%) were also reported, suggesting that conversion to roundabouts can significantly decrease fatalities and severe injuries. Further, the long-term effects (3-9 years) were reported to be even better than the short-term effect (1-2 years), mostly due to the adaptation effect.

In another study (Persaud et al., 2001), conversion of 23 intersections in the U.S. (7 states) from stop sign (19 instances) and traffic signal control (4 instances) to modern roundabouts was evaluated. Intersections included a mix of urban, suburban, and rural environments with both single-lane and multi-lane settings. Roundabout conversion significantly reduced crashes (40%) and led to an 80% reduction in injury crashes. Further, a strong effect was observed for reducing fatalities and incapacitating injury crashes, which decreased about 90% upon conversion to roundabouts. These effects can be due to the reduction in the speed of collision, and reduction of the specific conflicts happening at angular intersections (Persaud et al., 2001).

However, as Gross et al. (2013) argues, many of the conversions in the previous studies happened at unsignalised intersections and improvements may not be as significant for conversion of signalised intersections to roundabouts. Therefore, Gross et al. (2013) studied the effectiveness of converting 28 signalised intersections in the US to roundabouts. A period of 1-13 years before and 1-5 years after the conversion was studied. Significant reduction (at the 5% significance level) in crashes as a result of the conversion was reported. Safety benefits were reported to be larger for suburban than for urban conversions and for intersections with four approaches, as compared to three.

Overall, all the studies reviewed in this paper emphasised the effectiveness of converting intersections to roundabouts and consistently supported the evidence that roundabouts can significantly reduce crashes, especially injuries and fatalities, and can improve drivers' safety.

Exit-Lanes for Left Turn

The conventional intersections required alternative organised designs to manage the increasing traffic congestion around the world. The unique geometric feature of the exit-lanes for left turn (EFL) lies in mixed-use lanes, as shown in Figure 5.

Zhao et al. (2017) developed an optimised model to obtain effective operational approaches for intersections provided with EFL. This model collectively used the geometric design layout, main and pre-signal timing in an organised framework. The investigation found a significant effect in reducing the traffic delays and improved the intersection capacity, mainly under increased left turn demand. However, the operational safety of the designed EFL has to be examined prior to its actual implementation. Thus, the subsequent study utilised a driving simulator to investigate the driver behaviour and the impact of signs and markings on the traffic safety of EFL intersections (Zhao et al., 2015). The outcomes indicated that the drivers encountering

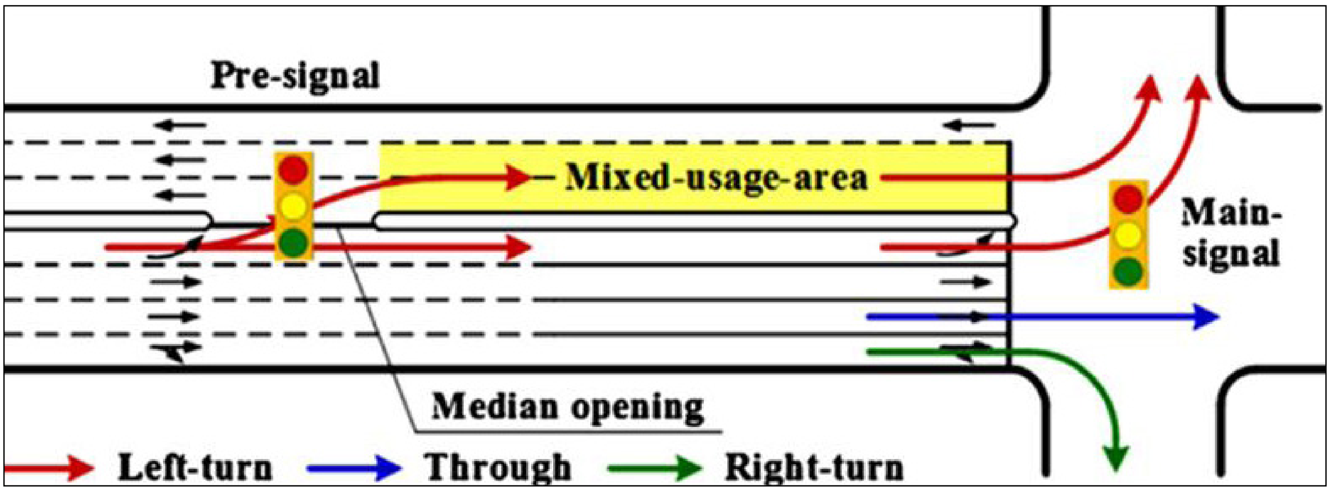

Figure 5: Geometric Features of the EFL (Zhau and Liu, 2017)

EFL intersections for the first time showed substantial confusion and uncertainty during their ride. In addition, the drivers unfamiliar with this operation may turn left using the conventional lanes, thereby posing an increased risk of crashes. On the other hand, Zhao et al. (2017) proposed a new EFL intersection design with a pre-signal at the median opening and a main signal at the intersection, which was found to be efficient in enhancing the intersection capacity with significant operational flexibility under heavy traffic congestion while taking the left-turn. However, the safety of the EFL was found to be ineffective due to an increase in red signal violations at pre-signal by 1.83% and wrong way issues under peak traffic hours that lowered the travel speed in the mixed-use area by 18.75%.

Left-Turn Bay Extension

The left-turn bay extension is an engineering measure to assist flexible turning movements with reduced probability of interference between other vehicles due to the formation of queues. Left-turn bay extensions provide space to facilitate comfortable deceleration and sufficient storage of turning vehicles as shown in Figure 6. This measure has been studied to evaluate the safety and operational impacts at signalised intersections (Tageldin et al., 2018). An experimental study investigated three treatment sites with individual left-turn lanes, and three matching control sites with untreated left-turn lanes. The study revealed a significant reduction in the frequency of crashes by 63.2% during left-turn movements after using the bay extension. Moreover, the lane blocking due to excessive flow of traffic was considerably reduced with the use of left turn bay extensions. Consequently, the average travel time decreased consistently, demonstrating enhanced safety impacts at intersections with extended left-turn lanes. Another study has examined the safety effectiveness with extended left-turn lanes at signalised intersections by considering injury severity and collision type. Guo & Sayed (2020) found substantial reduction in collision by 57.4% when comparing the before and after treatments. In addition, the rear-end collisions were observed to have reduced by 62.8% along with a 58.1% reduction in sideswipe collisions. More or less, the finding exhibited considerable enhancement in intersection safety in the presence of the extended lanes.

Contraflow Left-Turn Lane (CLL)

The contraflow left-turn lane (CLL) intersection is another engineering countermeasure recently put into operation at many signalised intersections that exhibit intensive left-turn demand. In CLL intersections, the left-turn lanes are designed and implemented into practice in the opposite lanes nearby the existing conventional left turning lanes. The CLL intersection design increases the capacity of vehicles turning left by allowing dynamic use of the opposite lanes. The left turning vehicles are provided with a median opening in the upstream to enable entry into the CLL. The left turning time window is controlled by installing a pre-signal at the upstream median area prior to entry into the CLL. The vehicle drivers are assisted through lane markings to help them identify suitable entry into the appropriate lanes. A detailed CLL design layout at a signalised intersection can be visualised in Figure 7. Wu et al. (2016) assessed effectiveness of CLL design on left-turn maneuvers at signalised intersections using an analytical model. This study examined five intersections to calibrate and validate the analytical model by collecting field data at six approaches and demonstrated that the CLL design led to improved capacity of left turn moving vehicles. However, the intersection capacity gained was uncertain due to the random movements of vehicles turning left. In addition, the CLL design reduced left-turn delay as compared to the existing conventional intersections. Krause et al. (2015) studied and compared the impact of the CLL design on intersection operational performance using a driving simulation approach. This

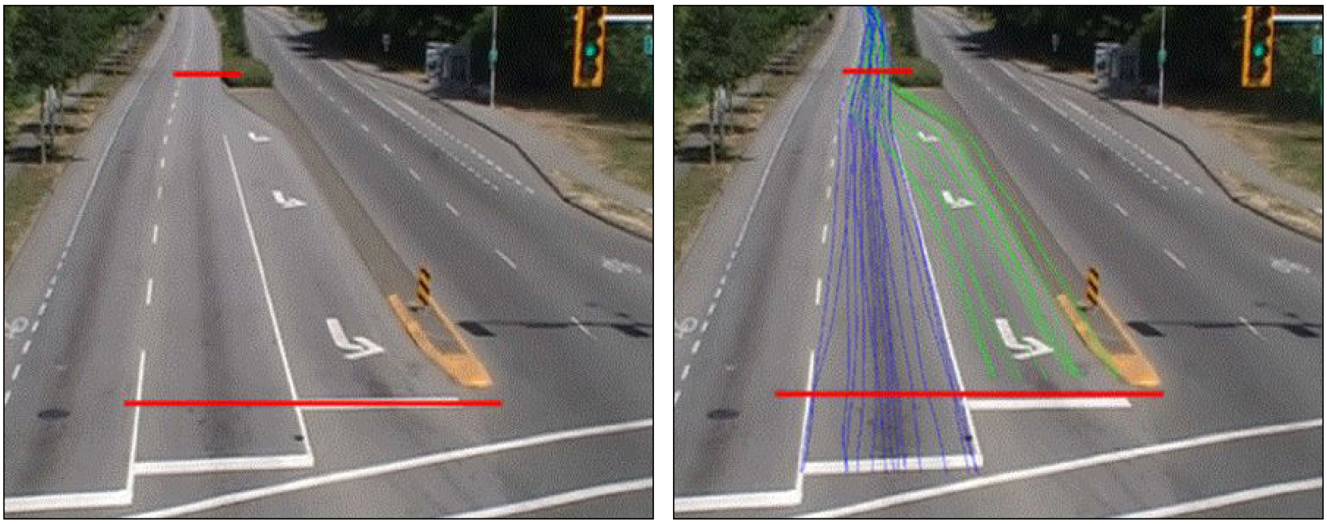

Figure 6: Representation of Left Turn Bay Extension (Tageldin et al., 2018)

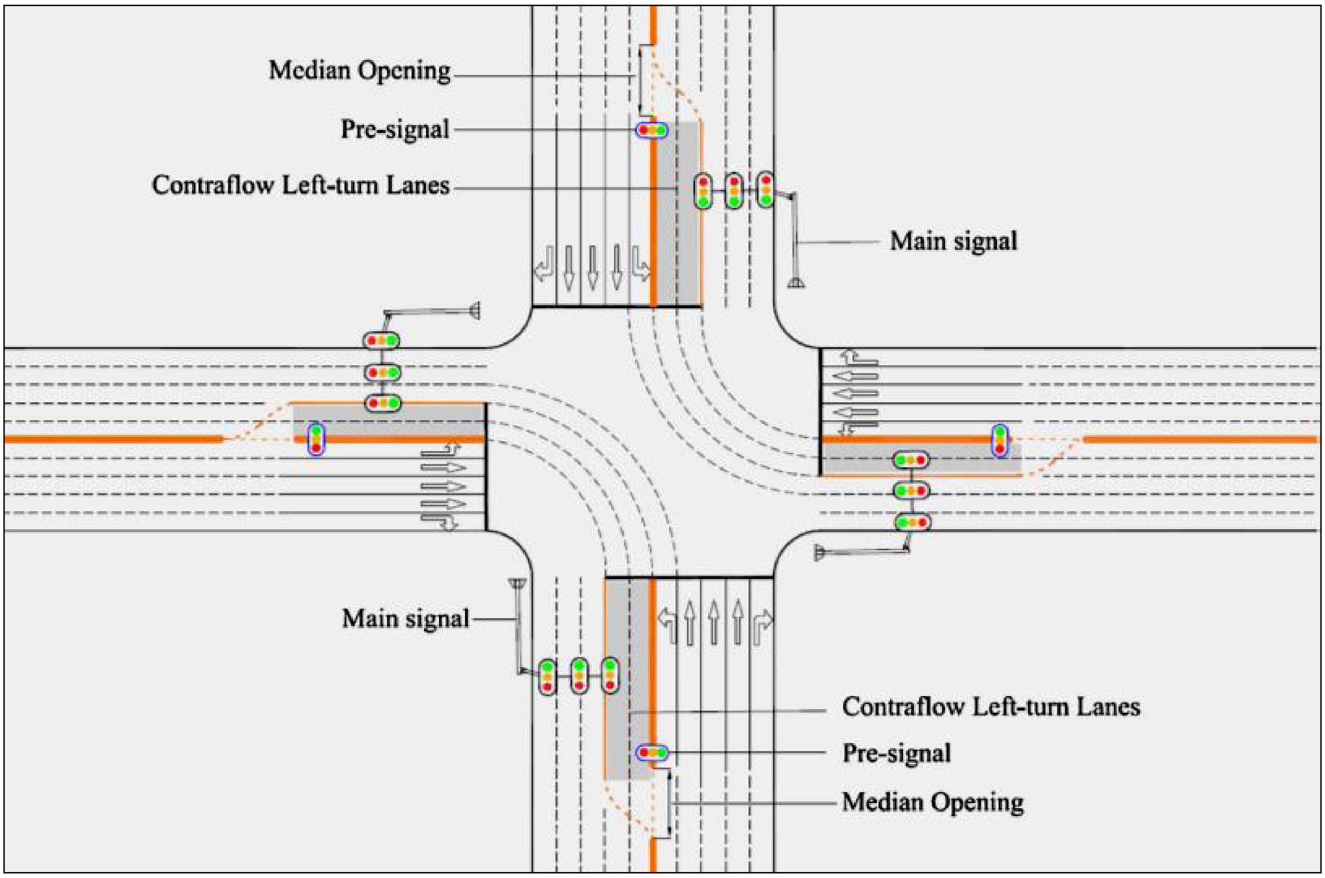

Figure 7: Detailed Layout of CLL Design at Signalised Intersection (Wu et al., 2016)

study also showed a reduction in delays to left-turning vehicles. Moreover, the operation capacity for the lane interchange increased using the CLL design. Shirgir & Mohammadinia (2020) evaluated left-turn capacity and the suitable time duration of incoming vehicle traffic at the signalised intersection with the CLL design using a simulation approach. Three intersections, one CLL design and two conventional ones were simulated and compared. This study showed that the CLL design reduced left-turn delays by 8% to 24% and thereby led to an improvement in the intersection's operational performance. However, the relative safety performance of the CLL intersection was not addressed.

Driver Warning Systems

Driver warning systems incorporate measures that inform drivers about the upcoming events on the roadway. These systems can either be supported via the infrastructure or through the vehicle. Emerging technology has made it possible to implement warning systems and decision support systems inside the vehicles that provide real-time feedback to drivers. Assistive prompts from In-Vehicle Warning Systems (IVWS) may present visual, auditory, or tactile alerts and information to drivers during left-turn situations. The use of Augmented Reality (AR) as a visual aid in the drivers' field of view is a novel sector of IVWS research. The suitable research studies focusing on this particular countermeasure have been mentioned in Table 3. A simulator-based pilot study that displayed a virtual projection of oncoming vehicles on a Head-Up Display (HUD) (Tran et al., 2013) (4 participants) showed that the gap acceptance varied across test subjects. Two subjects demonstrated fewer tendencies to accept gaps in presence of the driving aid, one subject seemed to be more aggressive with gap acceptance when the aid was present, and the last subject showed no difference in gap acceptance before and after the aid. Since a small sample size was used in this study, definitive conclusions cannot be drawn from these results. Future experiments using similar conditions and a larger sample size may prove to be beneficial in determining the effectiveness of a HUD-based AR aid in improving left-turn safety.

AR was used in another study to assess the effectiveness of cues to assist older drivers with the gap estimation of left-turns (Rusch et al., 2014). Sixty-four older participants involved in the study were presented with three pairs of intersections in a driving simulator and received AR cues in one out of the three pairs. Drivers had significantly shorter time-to-collision when the cues were presented. Further, gap response variation decreased when participants received cues and drivers' decision making was positively affected: they made 25% more responses

Table 2. Summary of Contributions w.r.t. Intersection Geometry.

Type	Lit.	Study	Sample Size	S.	Post-Implementation Results
Offset Left-Turn Lanes	Hutton et al., (2015)	Field	>1,000 left-turns; 44 lanes; 33 intersections	Y	↓ Sight obstruction from 85% to < 10% of the time at positive offset
	McCoy et al., (1992)	Field	N/A	Y	Positive offsets provide better sight distance than negative offsets
	Tarawneh & McCoy (1997)	Field	100 participants; 4 sites	Y	Positive offsets provide better sight distance than negative and zero offsets
Diverging Diamond Interchange (DDI)	Claros et al., (2015)	Field	6 interchange sites	Y	↓ Total crashes by 47.9% Eliminated fatal and injury crashes
	Hummer et al., (2016)	Field	7 sites; >3,000 crashes	Y	↓ Overall crashes by 29% ↓ Angle crashes by 67%
Roundabouts	Jensen (2013)	Field	332 sites	Y	↓ Crash leading to injuries (62%) and property damage only (24%) ↓ Fatalities (87%), severe injuries (58%), and slight injuries (59%)
	Persaud et al., (2001)	Field	23 intersections; 7 states	Y	↓ Crashes (40%) ↓ Injury crashes (80%) ↓ Fatalities and incapacitating injury crashes (90%)
	Gross et al., (2013)	Field	12 sites	Y	↓ Crashes significantly (5% significance level)
Exit-Lanes for Left Turn (EFL)	Zhao & Liu (2017)	Field	8 intersections; 22830 left turns	N	↓ Safety due to: - Red light violation at pre-signal -Wrong way violation at peak hours - Lower travel speed in mixed usage area
	Zhao et al., (2013)	Lab	2 intersections; traffic volume: 400, 640, 880 vehicles per hour	Y	↑ Intersection capacity ↓ Traffic delays safety: NA
	Zhao et al., (2015)	Lab	4 intersections; 80 participants; 16 did not complete; speed: 40 km/h	N	↑ Confusion/hesitation while taking EFL for the first time - No red light violated at pre-signal - Limited safety risk to unfamiliar drives
Left-Turn Bay Extension	Tageldin et al., (2018)	Field	3 intersections; 50km/h speed limit	Y	↓ Frequency of traffic conflicts by 63.2%. ↓ Average travel time ↑ Increases safety
	Guo & Sayed (2020)	Field	3 treatment sites; 31 comparison sites	Y	↓ Crashes by 57.4% ↓ Rear-end collisions (62.8%)
Contraflow Left-Turn Lane (CLL)	Wu et al., (2016)	Field	5 intersections; 6 approaches	N	↑ Improved capacity ↓ Delay to left-turn
	Krause et al., (2015)	Lab	3 intersections; 6 geometries	N	↑ Interchange throughput ↓ Travel time Suitable for high entering volumes, including high left-turn flows
	Shirgir & Mohammadinia (2020)	Lab	3 intersections i.e. 2 conventional and 1 contraflow lane	N	↓ Travel time by 6 to 16% ↓ Vehicle delay by 8 to 24%

(S. stands for Success (Effectiveness of the Countermeasure); Lit. Stands for Literature; Y: Yes; N: No.)

Table 3. Summary of Contributions w.r.t. Driver Alerts.

Type	Lit.	Study	Sample Size	S.	Post-Implementation Results
Driver Warning Systems	Tran et al., (2013)	Lab	4 participants	Y	↓ Gap acceptance (2 participants) ↑ Gap acceptance (1 participant) No difference in gap acceptance (1 participant)
	Nowakowski et al., (2008)	Field	20 participants	Y	↓ Time to make left-turn by 35%
	Bakhtiari et al., (2019)	Lab	49 participants	Y	↑ Driver anticipation by 17 percentage points
	Rusch et al., (2014)	Lab	64 participants; 15 did not complete	Y	↓ Time to collision ↓ Gap response variation - Drivers rated cues as not distracting 25% more responses (correct judgment of a safe turning opportunity)
	Calvi et al., (2020)	Lab	46 participants; 3 did not complete 4 routes i.e. 3 with augment-ed reality (AR) technology and 1 with no AR	N	↓ Waiting time by 43% ↑ Safe driver behaviour ↑ Number of safe turns ↓ Delays at intersection

(S. stands for Success (Effectiveness of the Countermeasure); Lit. Stands for Literature; Y: Yes; N: No.)

(correct judgment of a safe turning opportunity) in cued conditions. The positive effect of cuing also increased over time. Calvi et al. (2020) tested the potential of Augmented Reality (AR) technology using visual virtual information systems to improve left-turning movement of vehicles. The effectiveness of left-turn movements was assessed for vehicles installed with and without AR using a driving simulator setup. The results showed significant impacts of AR on the ride performance and safety towards left-turn movement. In addition, the AR improved the driver's ride behaviour during waiting time and decreased the average time required for a left-turn.

A comparison study between two warning systems (infrastructure-based and in-vehicle) on 20 participants (half of whom were older drivers) in a test-track traffic intersection evaluated the effectiveness of each warning system (Nowakowski et al., 2008). Participants were provided with two scenarios, one with a warning aid and the other with no aid and had to decide whether they had sufficient time to make a left turn through traffic. One system displayed an LED no-left-turn sign mounted on to existing traffic lights, while the other system used was an LCD screen mounted inside the vehicle (where a navigation system would normally be). It displayed an identical no-left-turn graphic, a countdown timer, and auditory feedback that activated when approaching an intersection. Results showed that there was no significant difference in the time it took for drivers to make left turns (turning rate) using either of the two interfaces. When using either system, the mean turning rate reduced by 35% when compared to left turns without warning aids. However, drivers found the LED no-left turn sign more intuitive and familiar than the in-vehicle LCD screen display, and it was easier to follow the LED sign since drivers were not required to look away from the road, as opposed to the in-vehicle warning system.

Another recent study utilised a driving simulator to investigate the effectiveness of visual and auditory warning alerts on older drivers' ability to anticipate threats while turning left at intersections (Bakhtiari et al., 2019). The results showed that across 8 scenarios, the in-vehicle warning system helped drivers anticipate a greater proportion of threats at intersections compared to the drivers that were not using the system (90% vs. 73% — a difference of 17 percentage points). Drivers demonstrated better hazard anticipation ability both before and after making the left turn at an intersection. In this study, the alerts were provided 3 to 4 seconds in advance of the intersection to provide drivers with sufficient time to process the information.

Discussion

This paper reviewed the literature on studies that assessed an array of existing countermeasures developed to help drivers make safer decisions when making left turns at signalised intersections. Results from observations, trials and tests conducted across these studies were summarised in this paper to highlight the effectiveness of each countermeasure. In this section, we aim to further present a succinct discussion of the countermeasures, and strengths and shortcomings of the reviewed studies, followed by directions of future work that could potentially benefit the ongoing research aimed to improve left-turn safety at intersections.

Among left turn displays, PLTs may be the most conventional measure in place to manage left turns at signalised intersections (Pline, 1996; Rune, 2009). An exclusive left-turn signal allows drivers to safely maneuver through an intersection without having to look for gaps in oncoming traffic, since drivers in adjacent and opposite lanes who are going straight have to wait at a red light for the duration of a protected green arrow. Some studies reviewed in this paper do show favourable results for the effectiveness of PLTs; however, some limitations must be addressed. Although the implementation of PLT yielded a significant reduction in left-turn crashes by 77% (Chen et al., 2015), it is difficult to determine whether the PLT resulted in an increase in other types of crashes and intersection traffic delays, because the experiment was conducted in a populated urban setting with a high density of vehicles and pedestrians alike. Another concern with PLT measures is the “yellow trap”, which may be a transition period between the protected phase (green left arrow) and permissive phase (no green arrow/standard circular green for through traffic), where drivers face a dilemma to clear the left-turn or come to a halt. FYAs may be a good form of left-turn countermeasure that can tackle this problem, as they help drivers become better informed on when to make a left turn after yielding to oncoming traffic. However, research has shown limited support for the effectiveness of FYAs, as some studies demonstrated little to no left-turn safety improvement over PLTs, and in some cases, an increase in crash rates. In some countries, there is no transition to a permissive phase and left turns only occur during protected left turn signal phases. In addition, the installation of digitalised countdown timers was found to decrease red light violation and hence it may lead to safer left-turn manoeuvres. Additional research is required to systematically explore the effectiveness of DCT at improving drivers’ perception behaviours while turning left at intersections.

Intersection geometry is an important consideration during road design as it can play a vital role in determining traffic safety. Drivers’ comprehension of traffic and general intersection safety may also depend on how roads and lanes are designed. Studies on offset left-turn lanes have shown that they are effective at reducing sight obstruction during left-turn maneuvres, and that positive offsets may provide drivers with better sight distance than negative offsets. However, as all intersection design measures, implementing an offset lane purely for the sake of improving left-turn safety may be unreasonably expensive, infeasible, and requiring much broader roadways. Offsets may have the potential to be a better left-turn safety measure if incorporated into intersection design from infancy, rather than as a re-design strategy. For example, the design of DDIs can actually result in low infrastructure costs during the long-term. Additionally, while they may be confusing for new drivers to follow, DDI’s may be a potential measure for reducing crashes and traffic delays at intersections. Researchers have shown uncertain outcomes regarding the use of EFLs at signalised intersections. Specific research has exhibited that EFLs led to low intersection safety due to red light and wrong way violations during the peak traffic hours (Braitman et al., 2007; Preusser et al., 1998). Moreover, the drivers were found to hesitate while taking EFLs for the first time. Other studies (Guerrier et al., 1999) have shown a considerable decrease in traffic delays and an improved intersection capacity using EFLs. No studies have clearly demonstrated a benefit from EFLs in terms of improving safety while making left turns. Left-turn Bay extensions may be a useful safety measure at signalised intersections. The researchers found a significant decrease in crashes and in the average travel time to make left-turn movements (Bao & Boyle, 2009; Romoser & Fisher, 2009). Contraflow left turn lanes have shown significant decrease in average travel time to take left-turn and increased intersection capacity (Romoser et al., 2013; Schneider et al., 2016; Brewer et al., 2014). Across the board, studies have failed to effectively compare the broad range of intersection geometry approaches that are available to improve driver safety while navigating left turns at signalised intersections. Future research should systematically compare contraflow lanes with left turn exit lanes and left turn bay extensions to demonstrate which may be a better situational fit. Relatedly, research should also explore the variable impact of these countermeasures at rural versus urban intersections.

Table 4. Summary of Advantages and Disadvantages of the Reviewed Countermeasures

Safety Measure	Advantage(s)	Disadvantage(s)
Left Turn Signal Displays		
Protected Left Turns	-Protects left-turning drivers from intersection conflicts (Agent et al., 1995) - Can minimise disruption of through traffic	"Yellow trap", where drivers may not realise that the oncoming traffic may not stop "
Flashing Yellow Arrow	-May reduce left-turn crashes -No "yellow trap" as compared to PPLTs	-Limited support for their effectiveness, there are studies that show no improvement over PPLTs or show an increase in the crash rate -↑ Driver confusion
Digital Countdown Timers	-Improved intersection capacity -Traffic delays may get reduced due to assistance in better understanding the traffic flows -May assist drivers to take decision within the displayed time units	-RSCD may not significantly improve intersection safety over longer term -Some studies reported increase crash rates at intersection with GSCD -Drivers may speed up aggressively when GSCD is provided, thereby increasing crash probability
Intersection Geometry		
Offset Left Turn Lanes	-Improves visibility of opposing lanes	- Requires broader roadways
Diverging Diamond Interchange	-Low infrastructure costs -↓ Crashes, especially angle crashes (Hummer et al., 2016) and left turn right angle crashes (Chilukuri et al., 2011) -↓ Traffic delay and traffic queuing (Chilukuri et al., 2011)	↑ Travel time due to slow speed through the crossover - Confusing for new users - Can lead to wrong-way crashes (Claros et al., 2015)
Roundabouts	-Can discharge traffic more efficiently (Hallmark et al., 2010) -Can reduced speed of collision (Persaud et al., 2001) -Can reduce specific angles at which the collisions happen (Persaud et al., 2001) -Can be combined with traffic signal control (Tracz & Chodur, 2012) -May lead to more fuel efficiency -Cheaper compared to signalised intersections -↓ Crashes, injuries, and fatalities -↓ Drivers approach speed	- May need a larger land - May be harder for pedestrians to cross - May be harder to figure out who has the right of the way - Lane sharing can be difficult with super sized trailers and trucks
Exit Lanes for Left Turn	-Can increase signal capacity under heavy left turn traffic conditions	- May increase red light violation at pre-signal, thereby affect safety -Peak hours may results into wrong way violation
Left Turn Bay Extension	-May decrease the average travelling time -Reduction in the rear end and sideswipe collision	-Drivers may be less familiar, thereby lead to wrong way movements
Contraflow Left Turn Lane	-Can increase the capacity of vehicles turning left that may reduce traffic delays -May enhance intersection operational performance	-May cause crashes when pedestrians unable to look in both directions

Safety Measure	Advantage(s)	Disadvantage(s)
Driver Alerts		
Driver Warning Systems	-Provide real-time feedback -Can be manipulated to have different forms (e.g., visual, auditory, or tactile) which can affect cognition differently -The sensitivity of these systems can be easily customised	-Can be expensive to implement and maintain -Can be distracting -May be prone to false alarms -More field research is required to deter- mine effectiveness -Such systems can sometimes experience lag and latency in real-time thereby compromising safety -Can lead to driver complacency

Roundabouts were another countermeasure reviewed in this paper. Converting intersections to roundabouts was shown to highly increase safety. In fact, the results were consistent across different studies with different durations (including long-term), all of which emphasised the effectiveness of roundabouts. Roundabouts can significantly reduce speed of collision, while discharging traffic efficiently (Hallmark et al., 2010). Therefore, roundabouts were found to successfully reduce fatalities and injuries due to left turns in the reviewed studies (Persaud et al., 2001). One drawback of the roundabouts may be that it would be harder for both pedestrians and drivers to decide when to enter the roundabout. One area that can be investigated in the future research is the effectiveness of combining roundabouts and signals. This measure has not seen much attention in the literature and may improve safety by combining benefits of both signals and roundabouts. Further, studies on conversion of signalised intersection to roundabouts were much more limited (Owais et al., 2020), as pointed out by Gross et al. (2013). Future work would benefit from evaluating the effectiveness of such conversion in different situations with varying levels of traffic. Warning systems have proven to be promising at alerting drivers either through the infrastructure or in-vehicle. IVWS that provide drivers with real-time audio/visual feedback have a lot of potential to be an effective form of left-turn countermeasure, as visual warnings on a HUD, for example, may assist drivers in immediately observing risk without losing focus on the road (Wege et al., 2013). When paired with auditory alerts, IVWS may be a great countermeasure as it can provide sound signals to ensure that drivers safely receive warnings regardless of where their visual focus is. All the studies on IVWS that were reviewed in this paper showed overall positive post-implementation results. However, studies have also shown that drivers found warning systems to be distracting and experienced lag and latency. IVWS can be expensive to implement and maintain but that could change as further advancements are made in the future. AR technology led to increase in number of safe left-turn movements with reduced waiting time at the intersection (Clapp t al., 2011). Although driver alert systems have potential as an effective form of left-turn countermeasure, such systems are still in their infancy and therefore require further research and development.

Another measure that may improve left-turn safety is pavement markings. A pavement marking is a visible message or graphic, or a combination of both, printed on the road surface upstream of an intersection that is meant to warn drivers of an upcoming signal (Elmitiny et al., 2010). The most common form of pavement marking is a left-turn arrow on a left lane that indicates drivers to move over to or stay on that lane if they want to make a left at the upcoming intersection. Pavement markings are used as countermeasures in several areas of traffic safety including pedestrian safety (Yan et al., 2007; Yan et al., 2009). To the best of our knowledge, research evaluating the effectiveness of pavement markings as safety measures for left turns are limited and we could not find one in our review. Therefore, there is a need for further research to concretely determine their effectiveness towards mitigating left-turn crashes or conflicts. In summary, each of the reviewed countermeasures has its own advantages and disadvantages as well. Table 4 summarises possible advantages and disadvantages w.r.t. various countermeasures.

Limitations

Our research approach has several limitations. This study focuses primarily on reducing crash occurrence, rather than preventing severe injuries, which limits the current assessment to contemporary design that aims to align with Safe System principles. The search process might not have covered all the existing literature, despite our best effort to be comprehensive in our review. For example, despite our attempts to include the most popular or common archival databases and online sources in our search process, we have not included international archives such as the CMF Clearinghouse (http://www.cmfclearinghouse.org/) or SafetyCube Decision Support System (https://www.roadsafety-dss.eu/). Multiple factors could have affected the validity of each study or could have led to inconsistencies across different studies. For example, type of intersections (signalised vs. unsignalised), traffic flow, time of the day, and experimental method could have all affected the results of each study. A meta-analysis would be useful to separate the effects. Some of the countermeasures had limited literature available. Different studies used different approaches and methods to study the effectiveness of the countermeasures. Further, confounding factors were not controlled in some of the reviewed studies. A comparison between different categories of countermeasures to evaluate which was more effective was inconclusive. Long-term effectiveness of many of the safety measures could not be evaluated due to lack of, or limited research on them. The scope of study is related to countries with driving on the right-hand side of the road only. While many of the reviewed papers were from North America, a subset of papers belonged to other continents, where driving or traffic behaviour might be different (e.g., mixed/heterogeneous traffic conditions involving both motorised and non-motorised forms of transport vs. more homogeneous systems with largely motorised transportation). Although this factor could have affected the results of each study and effectiveness of each countermeasure, investigating how findings were affected by driving/traffic behaviour was beyond the scope of this review.

Conclusions

Left turn crashes can happen at high speeds and at specific angles that can lead to severe injuries and fatalities. To reduce these crashes and improve safety, a variety of countermeasures for left turns have been designed and evaluated. This paper presented a review of the literature on engineering left-turn countermeasures. Relevant studies on left-turn displays (protected left turns, flashing yellow arrows, and digital countdown timers), intersection geometry-based measures (offset left-turn lanes, diverging diamond interchanges, roundabouts, exit lanes for left turn, left turn bay extensions, and contraflow left turn lanes) and driver alerts (in-vehicle and infrastructure driver warning systems) were discussed. Although all countermeasures had varying levels of effectiveness, it was found that protected left turns, roundabouts, and warning systems were consistently effective in increasing left-turn safety. This review has identified digital countdown timers, left turn lane extensions and bays, and driver warning systems as areas where much more research is required. Future research should also examine the long-term effectiveness of these countermeasures, both individually and in combination with each other.

Author Contribution

All authors reviewed the results and approved the final version of the manuscript.

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Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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