

Engineering Countermeasures for Red-Light Running: A State-of-the-Art Review

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Abstract

Red-light running poses a critical safety challenge at signalized intersections, driving extensive research into engineering and enforcement countermeasures. This review paper focuses on engineering countermeasures, classifying them into five functional categories: (1) improving signal visibility and conspicuity, (2) enhancing drivers' awareness and likelihood of stopping, (3) optimizing signal timing and operations, (4) eliminating the need to stop, and (5) mitigating dilemma zone conflicts. The review reveals that the effectiveness of red-light running countermeasures is heavily dependent on contextual factors such as geographic location, traffic dynamics, driver behavior, and geometric design. A countermeasure that is effective in one setting may yield mixed or even adverse results in another. This review also highlights that even well-regarded interventions can lead to unintended consequences if not implemented properly, emphasizing the need for post-implementation monitoring. The most effective countermeasure against red-light running is site-specific, and the literature summarized in this paper can serve as a valuable guide for practitioners in selecting the most appropriate strategy for their unique context.

Keywords

Red-Light Running, Engineering Countermeasures, Safety, Dilemma Zone

1. Introduction

Red-light running is a critical safety concern at signalized intersections as it can lead to serious injuries and fatal crashes. According to the Federal Highway Administration (2024), fatalities from red-light running in the U.S. increased by over 30% between 2017 and 2021 [1]. The Insurance Institute for Highway Safety reported that the U.S. experienced 1,149 deaths and 107,000 injuries resulting from

red-light running (RLR) crashes in 2022 [2]. Safety issues associated with red light running are not limited to the U.S. but are prevalent in many other countries worldwide. In China, for example, 750 fatalities were reported due to red-light running between January and October 2012, despite strict prohibitions against entering intersections during the yellow light [3]. Even with rigorous enforcement of traffic rules and regulations, red-light running remains a widespread issue in numerous countries and cultures [4]-[8]. RLR crashes occur when a vehicle enters an intersection during the red interval, often resulting in right-angle collisions with cross-street traffic. These crashes pose a heightened risk, as vehicles have significantly less structural protection on their sides compared to the front and rear. Additionally, red-light runners may exhibit rapid acceleration to beat the signal or clear the intersection, further increasing the crash risk. These factors can increase the severity of red-light running crashes, particularly endangering vulnerable road users such as motorcyclists, pedestrians, and bicyclists [9]. It is reported that about half of all fatalities in RLR crashes involve these vulnerable road users, or occupants in other vehicles (not at fault) [10]. Given the severity of such crashes, extensive research has been conducted to understand the factors contributing to red-light running, evaluate the effectiveness of potential countermeasures, and assess the impact of various enforcement efforts and public awareness campaigns over the past few decades. Nonetheless, the safety threat posed by red light running remains a pressing concern and will likely continue to be a significant concern for the foreseeable future.

Red-light running is the result of drivers' complex decision-making processes during the yellow interval. It can be both intentional and unintentional [11]. Intentional red-light running typically occurs when drivers perceive a lower risk of crashing or getting caught by law enforcement. Impatience caused by traffic congestion or excessive delays can also contribute to this dangerous driving behavior [12]. Additionally, drivers are more likely to run red lights when closely following another vehicle that has already done so, leading to a sequence of red-light violations [13]. Traveling through closely spaced coordinated traffic signals can also create an expectation among drivers for continuous green lights, which can result in multiple instances of red light running. On the other hand, unintentional red-light running can occur due to factors such as failure to perceive traffic signals, distractions while driving, or confusion [11]. Additionally, the inability to stop due to high speed, steep downhill slopes, poor signal visibility, or adverse weather conditions can contribute to this dangerous driving behavior [12]. Moreover, engineering factors such as insufficient duration of the yellow interval can create a dilemma for drivers, forcing them to choose between stopping or proceeding, which can lead to unintentional red-light running [14].

Given the complexity of red-light running behavior, no single countermeasure can adequately address this issue. Over the past decades, numerous countermeasures have been developed and shown positive outcomes in mitigating risks asso-

ciated with red-light running. Proven and effective countermeasures to date can broadly be categorized into two main types: 1) engineering countermeasures and 2) enforcement countermeasures [13]. Different countermeasures have been applied in different settings to address red-light running issues, each showing varying levels of impact on reducing these crashes. Understanding which countermeasures are suitable for specific circumstances, along with their potential advantages and associated issues, is crucial to ensuring the utmost safety and efficiency at signalized intersections.

This paper aims to provide a comprehensive overview of various engineering countermeasures implemented to date to mitigate red-light running and its associated crashes. It examines the reported performance of these measures, evaluates their effectiveness in reducing both red-light running and related crashes and explores any potential issues with their implementation. While red-light running has been a longstanding concern, many existing reports and literature may not reflect the latest research findings and advancements in the field. A comprehensive review is essential to consolidate current knowledge and previous research, facilitating a better understanding of research trends and identifying gaps in this area.

2. Systematic Literature Review

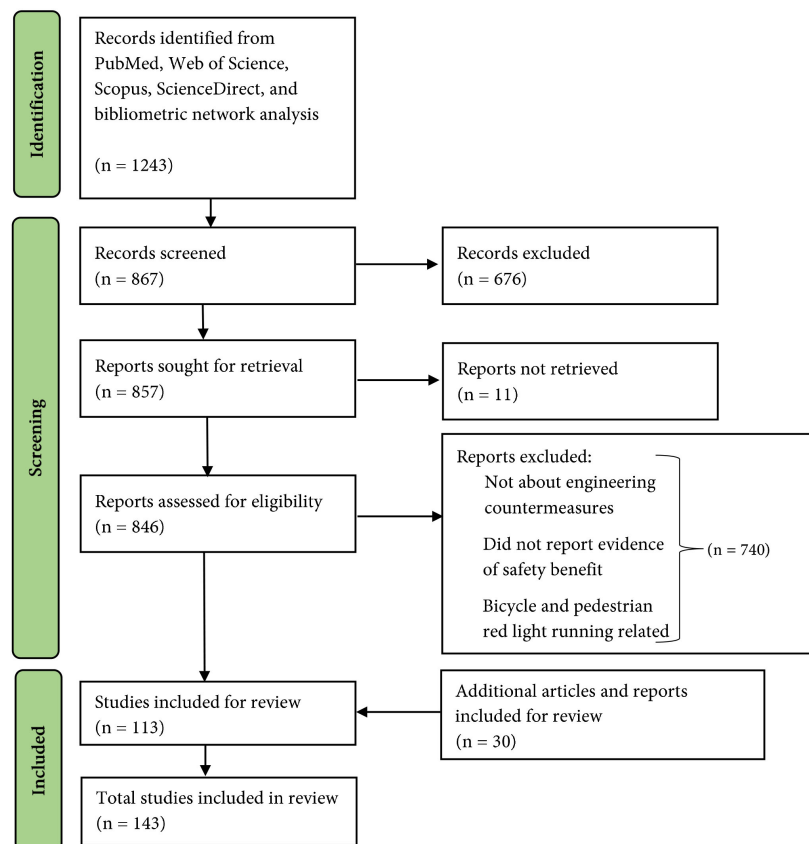


Figure 1. Systematic selection process of articles and technical reports in this review paper.

A thorough literature search was performed across multiple databases, including PubMed, Web of Science, Scopus, and ScienceDirect, to identify research articles and technical reports on red-light running until June 2024. Additionally, bibliographic network analysis tools, which can generate detailed visualizations of related publications from bibliography, were utilized to trace relevant studies. However, only studies that reported the safety performance of one or more engineering countermeasures for red-light running were included in this paper. Articles focusing on pedestrian and bicycle red-light running were excluded from the literature review, but federal and state-funded technical reports were included. Following a thorough search and screening process, 113 journal articles and technical reports that reported the safety performance of various engineering countermeasures were selected. Additionally, to discuss the theoretical understanding of these countermeasures, more supporting articles were incorporated. **Figure 1** shows the systematic selection process of articles in this review paper.

Figure 2 illustrates the number of publications containing the keyword “Red-Light Running” retrieved from the Scopus database between 1980 and 2024, demonstrating a consistent upward trend in research interest and scholarly focus on this topic.

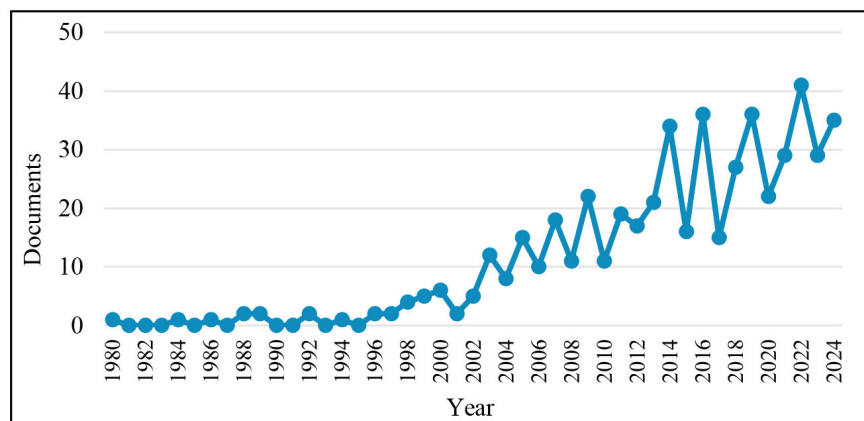


Figure 2. Growing research trend on red-light running (1980-2024).

3. Red-Light Running Countermeasures

3.1. Engineering Countermeasure

Engineering countermeasures involve additions, modifications, or adjustments of intersection geometries or traffic control devices to reduce red-light running and crashes. While some literature addresses engineering countermeasures as methods for mitigating only unintentional red-light running, this is not always true. Engineering measures can also influence intentional red-light running behavior. Moreover, measures like the all-red interval do not focus on reducing red light running itself but rather aim to mitigate the risk associated with it. Available engineering countermeasures can be broadly grouped based on their functionality

in reducing red-light running and its associated risk. Inspired by the categorization provided by Hallmark *et al.* (2012), this paper divides engineering countermeasures into five categories based on their functionality as shown in **Table 1** [15]. For example, measures such as LED signal lenses, retroreflective borders on signal backplates, and programmable signals are commonly used to mitigate issues related to signal visibility and conspicuity [16]-[19]. To improve drivers' awareness and likelihood of stopping, countermeasures like 'signal ahead' signs, advance warning flashers, pavement markings, and countdown timers have shown potential [20]-[22]. The adjustment of the yellow and all-red intervals or cycle lengths has also been used to reduce red-light running and the risk associated with it [23] [24]. Additionally, strategies like constructing roundabouts, removing unwarranted traffic signals, or implementing coordinated signal operations have also shown promise in reducing RLR crashes by eliminating the need for frequent stops [25]-[27]. Recently, advancements in sensor technologies have led to the popularity of dilemma zone protection systems that can effectively improve red light running safety [28]-[30]. A detailed discussion of the engineering countermeasures outlined in **Table 1** will be provided in section 4, literature review of engineering countermeasures.

Table 1. Engineering countermeasures for reducing red-light running crashes.

Improve traffic signal visibility/conspicuity	Improve drivers' awareness and likelihood of stopping	Improve signal timing and operations	Remove the need to stop	Protect vehicles from dilemma zone conflicts
Provide a signal head for each through-lane approach	Install 'signal ahead' signs and pavement markings	Adjust the yellow interval length	Coordinate signal operations	Dilemma zone protection system with signal control strategies
Install backplates	Install advance warning flashers	Adjust signal cycle length	Unwarranted traffic signals	
Install retroreflective borders to existing backplates	Install in-vehicle warning systems	Provide or adjust all-red interval	Replace signalized intersections with roundabouts	
Adjust the placement of signal heads	Install traffic signal countdown timers			
Larger signal displays	Signal flashing before phase transition			
Install programmable signal/visors or louvers	Install transverse rumble strips			
Install LED signal lenses	Improve pavement surface condition			
Improve sight distance to the signals				

3.2. Enforcement Countermeasures

To address the red-light running issue, enforcement methods have also been implemented to compel drivers to adhere to traffic laws through fines or citations

[14]. Enforcement methods can be categorized into two parts: officer-involved enforcement and camera/automated enforcement [31]. The officer enforcement method is achieved by increasing the presence of law enforcement officers and installing confirmation lights at signalized intersection intersections. Camera/automated enforcement method (e.g., red-light running camera), is accomplished by installing an automated camera at the intersection, capable of capturing images of red-light runners and their license plates, followed by issuing citations via mail [31] [10]. For the past 30 years, red light running cameras have been utilized in the U.S. and has gained popularity among local and state agencies [32]. Many studies have shown that red-light running cameras can effectively reduce right-angle crashes by discouraging drivers from running red-light at signalized intersections [33]-[37]. However, it has also been shown that red-light running cameras can increase rear-end crashes [38]-[43]. Applying engineering countermeasures (rather than enforcement countermeasures) is a preferable approach to reduce red light running crashes due to their sustained impact and cost-effectiveness.

4. Literature Review of Engineering Countermeasures

4.1. Improving Traffic Signal Visibility/Conspicuity

Visibility refers to the property of a traffic signal that allows it to be detected by humans under various conditions, whereas conspicuity refers to its ability to stand out against similar but irrelevant signals [44]. Visibility and conspicuity of signal heads are crucial for drivers to see the signal light, react appropriately, and perform required maneuvers. If a signal is not visible, drivers may be late in identifying the signal phase and transition, potentially failing to stop safely and running the red light. Improving signal visibility can be one of the fastest and low-cost methods to reduce red-light running.

Improving visibility through retroreflective borders and backplates on signal heads has shown effectiveness in reducing RLR violations. Miska *et al.* (2002) evaluated the impact of enhanced traffic signal conspicuity on intersection safety in British Columbia through a two-phase project. Phase 1 focused on improved signal head design, while Phase 2 added yellow reflective tape to signal backboards. An Empirical Bayes method using insurance claim data showed that 19 out of 25 intersections experienced a reduction in claims, with reductions ranging from 2.8% to 60.7%. On average, the improvements led to an estimated 14.8% decrease in total claims [16]. A Federal Highway Administration report evaluated the application of 3-inch yellow retroreflective borders on existing signal backplates at three signalized intersections in Columbia, South Carolina [18]. The analysis showed a decrease of 28.6% in overall crashes, 36.7% in injury-related crashes, and 49.6% in crashes occurring late at night or early in the morning. However, the study used a basic before and after crash count procedure without applying any statistical methods. Dias and Dissanayake (2014) conducted a cross-sectional and before-and-after study using two intersections in Manhattan, Kansas, to examine

the effect of 2-inch yellow retroreflective borders on existing signal backplates [45]. The results showed that retro-reflective backplates effectively reduced red-light violations for through and left-turning traffic. However, Moreland *et al.* (2024) conducted a cross-sectional and before-and-after study on 109 signalized intersections in Minnesota and found that adding retroreflective signal backplates did not lead to a statistically significant reduction in crashes compared to similar intersections without retroreflective borders [19]. However, the study suggested that a possible reason behind the result is that the treated signals already had good visibility, which meant the added retroreflective borders did not enhance their visibility/conspicuity significantly. Reyad *et al.* (2017) conducted a before-and-after study using the Empirical Bayes (EB) method at two signalized intersections in Edmonton, Alberta, Canada, to evaluate the impact of yellow reflective tape around existing signal backplates [46]. The study revealed a statistically significant 24% decrease in the average number of rear-end conflicts per hour and a 24.5% reduction in the average number of total conflicts per hour. Similarly, El-Basyouny *et al.* (2013) evaluated improved signal visibility using a combination of upgrades (increased signal lens size, reflective tape, and additional signal heads) at 22 signalized intersections in Surrey, British Columbia, Canada [47]. The study found a 20% reduction in severe collisions at nighttime and a 10.6% reduction in daytime PDO collisions.

Scopoline *et al.* (2018) analyzed the safety effect of installing separate signal heads for each lane at 25 signalized intersections in Wisconsin using simple before and after crash count comparison and EB method [48]. The study reported notable reductions in right-angle and rear-end crashes. However, the reduction in rear-end crashes identified using the EB method did not reach statistical significance at the 90% confidence interval. Tydlacka (2011) evaluated two signalized intersections equipped with lighted stop lines and LED-outlined signal backplates in Houston, Texas [49]. A statistically significant reduction in red-light running was observed with LED-outlined signal backplates. At the intersection with lighted stop lines, a reduction in red-light running was also noted; however, it did not achieve statistical significance. Sayed *et al.* (2007) evaluated signal visibility enhancements such as larger lenses, retroreflective tape, new backplates, and additional signal heads at 139 urban intersections in British Columbia, Canada using the EB method [50]. Results showed statistically significant reductions in property damage only (PDO) crashes in both daytime and nighttime conditions. Severe crashes also showed a 2.6% decrease but were statistically nonsignificant. In a previous study, Sayed *et al.* (1998) tested larger signal heads with reflective borders at 10 Canadian intersections, finding mixed outcomes with total accidents decreased at 7 sites but increased at 3, and severe accidents declined at 8 sites rose sharply at 2 [51].

Jami *et al.* (2011) conducted a before-and-after crash analysis using the EB method to evaluate the safety impacts of LED traffic signal installations at eight signalized intersections in Charlotte, North Carolina [17]. The study found an in-

crease in traffic accidents following the implementation of LED signals. However, the findings were limited by a small sample size and did not account for the effects of different crash types or weather conditions. Srinivasan *et al.* (2013) also evaluated the safety impacts of LED traffic signal installations at 282 signalized intersections in Charlotte, North Carolina, using EB analysis [52]. For three-leg intersections, Crash Modification Factors (CMFs) ranged from 1.016 to 1.177, indicating a non-significant increase in crashes. For four-leg intersections, CMFs ranged from 0.827 to 1.091, with five out of eight CMFs below 1.0, showing statistically significant reductions in rear-end crashes across various lighting conditions. Eustace *et al.* (2010) analyzed LED signal installations at 10 urban intersections in Middletown, Ohio, and found a 71% increase in total crashes, indicating a deterioration in safety [53]. However, the authors acknowledged that the study's small sample size (8 treated and 2 untreated intersections) could limit the generalization of its findings.

The mixed results reported in the literature on improving traffic signal visibility and conspicuity indicate that, due to the complex nature of red-light running behavior, simple signal visibility enhancements may not lead to noticeable improvements in red-light running safety unless there is a significant existing visibility issue. Nevertheless, existing literature recommends upgrading signal lights to LED technology as a potential measure for addressing red-light running due to their ability to enhance signal visibility during both day and night conditions [14] [15].

4.2. Improve Drivers' Awareness and Likelihood of Stopping

Drivers often encounter situations at signalized intersections where they misjudge the remaining time of the yellow light, their speed, or their distance from the stop line when the signal transitions from the green to the yellow light. By the time drivers realize they are about to violate the red light, they may lack sufficient stopping distance to come to a safe stop. This miscalculation may lead to red-light running. Several engineering countermeasures have been tested to address this issue by providing drivers with additional information or by enhancing their maneuverability at the intersection. This section discusses engineering countermeasures designed to improve drivers' awareness and likelihood of stopping.

4.2.1. Installing "Signal Ahead" Signs and Pavement Markings

"Signal ahead" signs and pavement markings are placed upstream of a signalized intersection to alert drivers about an upcoming signal, especially in locations where available sight distance is limited for drivers [54]. Providing information about upcoming intersections ahead of time can help drivers become more attentive and better prepared to stop at intersections. **Figure 3** shows an example of "signal ahead" signs and pavement markings installed upstream of a signalized intersection in Auburn, Alabama.

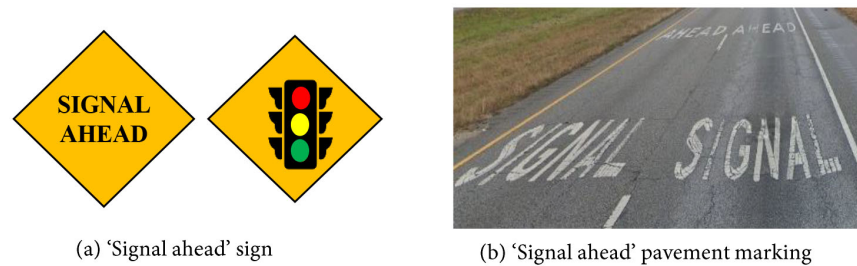


Figure 3. ‘Signal ahead’ sign and pavement marking at US-280 in Auburn, Alabama.

Wu *et al.* (2018) evaluated the performance of various intersection warning systems using a simulation approach. They found that pavement markings could reduce the risk of rear-end crashes but might increase the chance of red-light running, depending on vehicle speed [55]. Yan *et al.* (2009) used a driving simulator study with 42 drivers to assess the effectiveness of “signal ahead” pavement markings placed upstream of the intersection [20]. They found that the pavement markings effectively reduced risky decisions at intersections, shortened the Type-II dilemma zone, improved the deceleration rate, and decreased the likelihood of rear-end crashes and red-light running. Elmitiny *et al.* (2010) conducted a before and after driver behavior study at two signalized intersections in Orlando, Florida, and found that “signal ahead” pavement markings can effectively reduce red-light running rates [56].

Given their safety benefits and low associated costs, “Signal Ahead” signs or markings should be implemented as a standard practice at intersections with sight-distance issues to improve drivers’ decision-making and enhance awareness. Post-implementation monitoring should also be conducted to ensure that no adverse consequences result from its introduction.

4.2.2. Advance Warning Flashers

Advance warning flashers (see **Figure 4** as an example) are positioned upstream of intersections to inform drivers about upcoming phase transitions using flashing lights [21]. They typically activate a few seconds before the end of the green phase, providing an advanced indication of the upcoming signal change to help drivers come to a safe stop. Agent and Pigman (1994) conducted a comprehensive analysis incorporating survey data, crash history, and driver behavior to evaluate strategies for mitigating dilemma zone issues at high-speed signalized intersections. Their study compared the effectiveness of the Green Extension System (GES) and Advance Warning Flashers (AWFs) in improving safety. While GES was deemed effective and recommended for continued use, AWFs were advised for locations with a documented crash history or high crash potential. The study identified key factors for AWF implementation, including accident history, speed limit, truck volume, sight distance, roadway grade, red-light violation rates, traffic volume, and proximity to bridge decks [57]. Pant and Xie (1995) conducted an analysis of traffic flow data from two high-speed signalized intersections in Ohio to evaluate the impact of different advance warning signs equipped with flashers, including

PTSWF (Prepare to Stop When Flashing), FSSA (Flashing Symbolic Signal Ahead), and CFSSA (Continuously Flashing Symbolic Signal Ahead) and found that the effectiveness of these signs varied based on the approach geometry of the intersections [58]. The study also reported that PTSWF and FSSA could inadvertently encourage speeding on straight approaches, so caution is advised in their use. Sayed *et al.* (1999) assessed the impact of Advance Warning Flashers (AWF) using accident prediction modeling [21]. The study found that intersections with AWFs experienced a 10% reduction in total accidents and a 12% reduction in severe accidents, though rear-end accidents showed no significant reduction. The effectiveness of AWFs was also found to be varied with traffic volume, with lower volumes linked to higher accident frequencies and higher volumes showing reduced accident rates. Sunkari *et al.* (2005) evaluated the Advance Warning for End-of-Green System (AWEGS) through a field study at high-speed signalized intersections in Texas, noting enhanced dilemma zone protection and a 42% reduction in RLR violations [59]. However, Burnett and Sharma (2011) in their study of five high-speed signalized intersections in Lincoln, Nebraska found that advance warning flashers might increase the risk of RLR and rear-end crashes [60]. Farraher *et al.* (1999) reported a 29% reduction in RLR crashes with the implementation of active advance warning signs, including a 63% reduction in crashes involving trucks, though speeds and violations remain high at the studied sites [61]. Schultz *et al.* (2007) reported a statistically significant decrease in both speed and RLR violations after installing blank-out overhead dynamic advance warning signals [62].

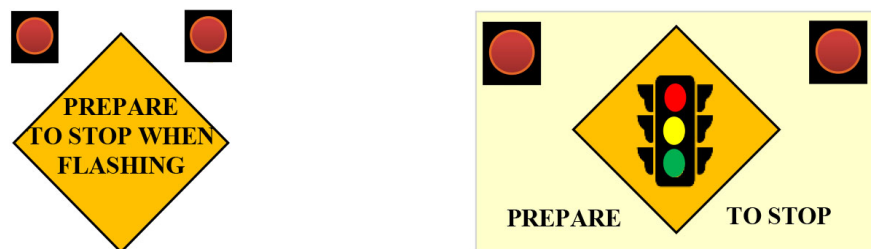


Figure 4. Advanced warning flasher example design.

Appiah *et al.* (2011) conducted a Fully Bayesian before-and-after crash analysis at 26 signalized intersections with AWFs in Nebraska [63]. The study found an 11.3% reduction in injury crashes, a 43.6% decrease in right-angle crashes, and an overall 8.2% reduction in total crashes, with a minor decrease in rear-end crashes. Wu *et al.* (2013) also found through a crash analysis of 28 intersections in Nebraska that reducing speed limits from 65 mph to 55 mph, combined with signal warning flashers, can effectively reduce the probability of injury crashes [64]. Zhao *et al.* (2016) analyzed the Advance Warning System (AWS) in Coordinated Signal Operation using data from nine signalized intersections and a simulation study [65]. Results showed significant reductions in rear-end, lane-change, and crossing conflicts, with nearly 70% of vehicles reducing speed upon encountering

the system.

The mixed results from evaluating Advance Warning Flashers (AWFs) suggest that while they have the potential to reduce red-light-running crash risk, they may also inadvertently encourage red-light-running or speeding behavior. As a result, AWF implementation should be limited to high-risk intersections and be monitored for any negative impact after installation.

4.2.3. In-Vehicle Warning System

In-vehicle warning systems function similarly to advance warning flashers, but the warning is delivered directly to the driver inside the vehicle. Current studies have been limited to simulation evaluations, but in the future, its field performance may be tested through vehicle-to-infrastructure (V2I) communication systems. Few studies have demonstrated the effectiveness of in-vehicle warning systems in reducing RLR violations. Yan *et al.* (2015) conducted a driving simulator study to evaluate the effectiveness of an in-vehicle audio warning system designed to alert drivers of potential red-light-running RLR violations at two-lane signalized intersections. The results demonstrated a significant 84.3% reduction in RLR violations [66]. Similarly, Bar-Gera *et al.* (2013) explored the impact of an in-vehicle audio and visual warning system to alert drivers approaching signalized intersections. The driving simulator study with 20 drivers showed a 96% reduction in RLR violations and a 70% decrease in driver indecision, resulting in more stable speeds and quicker intersection clearance [67].

Although research on in-vehicle warning systems remains limited and primarily confined to simulation studies, their potential to enhance driver attention and decision-making at intersections is promising. With advancements in vehicle-to-infrastructure (V2I) communication technologies, these systems are likely to be more effectively tested in real-world scenarios.

4.2.4. Traffic Signal Countdown Timers

Traffic signal countdown timers (TSCTs) are digital displays used in signalized intersections that show the exact amount of time remaining before the traffic signal changes to the next phase [22]. Many countries use TSCTs to help drivers in decision-making when signal transitions from green to yellow lights to reduce the dilemma zone issues. However, it is yet to be adopted in the United States. **Figure 5** shows the concept of a TSCT that shows the green time remaining before the signal transitions to yellow.

Research on signal countdown timers at signalized intersections has shown their influence on driver behavior. Islam *et al.* (2017) conducted a driver simulator study involving 55 participants to assess the effectiveness of green signal countdown timers (GSCTs) in the United States [68]. The findings revealed that the presence of GSCTs increased the probability of drivers stopping by 13.10%, while also reducing the deceleration rate by 1.50 ft/s². Similarly, Limanond *et al.* (2010) performed a traffic analysis and public opinion survey at intersections in Bangkok, comparing intersections with and without signal countdown timers (for both red

and green phases) [69]. Their results demonstrated a 22% improvement in start-up lost time and a 50% reduction in red light violations at intersections equipped with countdown timers. Additionally, the survey indicated that countdown timers reduced frustration among 64.4% of car drivers and 51.8% of motorcycle drivers during the red phase. Paul *et al.* (2022) explored the impact of GSCTs on dilemma zones at 10 signalized intersections in India, comparing 5 intersections with GSCTs to 5 without [70]. The study found that GSCTs reduced the length of both Type-I and Type-II dilemma zones and enhanced stopping behavior. Ni and Li (2014) evaluated green signal countdown devices (GSCDs) at four signalized intersections in China using a microscopic probability model [71]. In contrast, their results indicated that intersections with GSCDs had a 3 - 5 times higher probability of red-end collisions compared to those without. Dilemma zones at GSCD-equipped intersections were found to be shorter and located further from the stop line. Furthermore, drivers at these intersections accepted shorter following headways, indicating an increased risk of rear-end collisions. Rijavec *et al.* (2013) assessed the impact of countdown timers (for both green and red phases) at a signalized intersection in Slovenia using surveillance data and a public survey [72]. The authors observed a decrease in red light violations when countdown timers were active, and in the survey, 84% of drivers expressed positive opinions about their implementation. Devalla *et al.* (2015) also evaluated GSCTs by comparing two intersections in India, one with and one without GSCTs [73]. Their results showed that GSCTs reduced red light running but increased the speed of vehicles crossing the stop line during the yellow interval. However, Ibrahim *et al.* (2008) reported contrasting findings in Malaysia, where intersections with countdown timers experienced higher rates of red light running than intersections without [74].

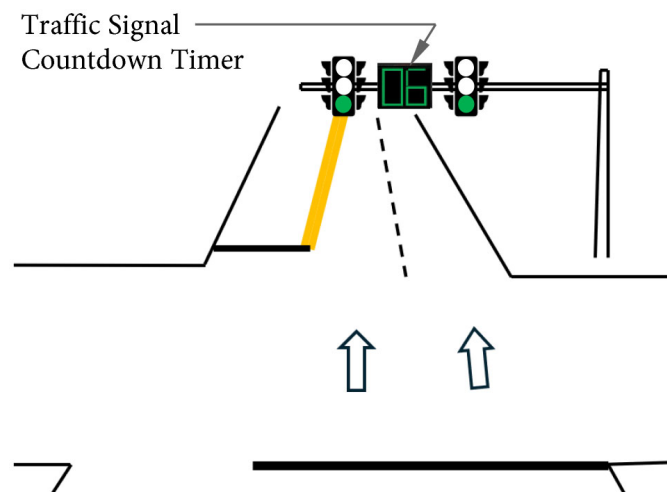


Figure 5. Traffic signal countdown timer.

Huang *et al.* (2017) analyzed field survey data on driver behavior at eight signalized intersections in Changchun, China, during both summer and icy winter

seasons [75]. Their findings indicated that the installation of CCTV cameras and countdown timers reduced abrupt acceleration and deceleration, leading to smoother intersection entries. Additionally, during winter, drivers exhibited a higher tendency to stop when both CCTV and countdown timers were present compared to when only one or neither was installed. In a previous study, Huang *et al.* (2014) analyzed driver behavior at six signalized intersections in Changsha, China, and discovered that a green signal countdown timer resulted in higher rates of stopping and deceleration compared to a green flashing system [76]. The countdown timer also significantly reduced the number of vehicles trapped in the dilemma zone.

Long *et al.* (2013) examined driver behavior at intersections with and without countdown timers in China, reporting that while the presence of a countdown timer increased instances of yellow light running, it also reduced aggressive stopping behavior [77]. In another study, Long *et al.* (2011) conducted a regression-based analysis of driver behavior at four signalized intersections in Changsha, China, and found that countdown timers increased the likelihood of drivers crossing the stop line during the yellow phase and contributed to a rise in red-light running incidents [78]. Ma *et al.* (2010) investigated the effects of green signal countdown timers (GSCD) at two intersections in China, revealing that their implementation led to increased vehicle entry speeds during the yellow interval and a significant reduction in red-light violations. The study further noted that GSCD eliminated the dilemma zone by enabling drivers to make earlier decisions and promoted smoother transitions between signal phases, effectively reducing sudden speed changes [79]. However, Chiou and Chang (2010) in a long-term study on driver behavior at intersections with green and red signal countdown timers, found that while these timers reduced the frequency of late stops, they also extended the length of the dilemma zone and introduced a potential risk of rear-end collisions [80]. The study also reported that despite improving intersection efficiency by reducing start-up delay, saturated headway, and cumulative start-up delay, no long-term safety benefits were observed. Lum and Halim (2006) performed a before-and-after analysis of driver behavior at a signalized intersection in China, reporting an initial 65% reduction in red-light running following the implementation of GSCD. However, this benefit diminished over time as red-light running rates returned to previous levels [81].

Although many studies have highlighted the benefits of traffic signal countdown timers (TSCTs), such as reducing red light running, improving stopping behavior, and mitigating dilemma zones, conflicting findings have also been reported. Aggressive drivers may exploit the precise timing information provided by TSCTs, leading to unintended consequences, such as increased speeding during the yellow interval and, consequently, more red light running. As a result, many researchers advise against their implementation, as the associated complexities, costs and possible negative outcomes may outweigh the potential safety benefits.

4.2.5. Signal Flashing before Phase Transition

Flashing signals, similar to AWFs, provide early information to drivers about the upcoming phase transition. However, while AWFs use roadside beacons located upstream to warn drivers, flashing signals involve the traffic light itself flashing for a couple of seconds before transitioning to the next phase.

Tang *et al.* (2016) conducted an empirical analysis of driver stop and go behavior at three high-speed rural intersections in China and found that the introduction of flashing green signals before the yellow light led to more conservative stopping but also slightly increased aggressive passing behavior [82]. Factor *et al.* (2012) surveyed 670 drivers in Israel about their perceptions of flashing green signals and found that while there was strong support for implementing such a system, many drivers did not fully understand its meaning or how to respond to it appropriately [83]. Despite the public support, the study recommended against the implementation of flashing green signals due to the increased risk of rear-end crashes. Köll *et al.* (2004) analyzed drivers stopping behavior at 10 signalized intersections in Austria, Switzerland, and Germany and found that flashing green signals before yellow light increased the number of early stops [84]. Newton *et al.* (1997) evaluated the Traffic Light Change Anticipation System (TLCAS) using a driving simulator with 41 participants [85]. This system employed flashing yellow signals in conjunction with a solid green light to indicate a phase change and found a reduction in RLR violations, abrupt acceleration, deceleration, and right-angle crashes. However, the system was also found to increase the dilemma zone length and the risk of rear-end crashes.

Although the primary objective of flashing signals is to provide drivers with early information about phase transition to promote safe stopping behavior, due to the complex nature of driver behavior it can introduce potential risks. This system may create confusion among drivers and could encourage aggressive behaviors. Given the high likelihood of such unintended negative consequences, the implementation of flashing signal systems may not be justified, as the potential risks could outweigh the cost and intended safety benefits.

4.2.6. Transverse Rumble Strips

Transverse rumble strips are grooved patterns provided horizontally on the road surface, offering both audible and physical warnings to drivers approaching an intersection. **Figure 6** shows transverse rumble strips located upstream of an isolated signalized intersection on a high-speed roadway in Alabama. To date, most applications and research on transverse rumble strips have been limited to freeway ramps, upstream of sharp curve sections, or stop-controlled intersections. However, their performance in reducing crashes at stop-controlled intersections can also be replicated at signalized intersections. Yang *et al.* (2016) investigated the effectiveness of combining “signal ahead” signs with transverse rumble strips at four signalized intersections in Alabama [86]. The study found that transverse rumble strips produce significant sound and vibration, effectively capturing drivers’ attention. This combination of visual and auditory cues led to a notable re-

duction in vehicle speeds approaching the intersections.



Figure 6. Transverse rumble strip (horizontal white lines) at US-280 & Grand National Parkway in Auburn, Alabama.

4.2.7. Improving Pavement Surface Condition

Enhanced pavement friction also improves vehicle control and reduces stopping distances, thereby helping drivers stop their vehicles in response to signals at signalized intersections, particularly on downgrades or in slippery conditions. Improved vehicle control, quicker deceleration, and reduced stopping distances, achieved by high surface friction treatment (HSFT) has the potential to reduce the likelihood of red-light running. Several studies have investigated the impact of pavement surface friction on crash frequencies at signalized intersections.

Sharafeldin *et al.* (2023) conducted an empirical analysis of intersection attributes and crash frequency, finding that increasing the pavement friction coefficient significantly reduced the frequency of property damage-only crashes at intersections [87]. In another study, Sharafeldin *et al.* (2022) found that higher pavement friction numbers were correlated with fewer severe injury crashes at signalized intersections in Wyoming [88]. Hussein *et al.* (2021) in their before-and-after crash analysis at 57 signalized intersections in Melbourne, Australia found that higher skid resistance is linked to fewer crashes under high traffic volumes conditions, although the trend reverses for low traffic volumes [89]. In previous studies, the authors reported that increased rutting and skid resistance can lead to fewer crashes in both wet and dry conditions [90] [91]. Similarly, Saplioglu *et al.* (2013) analyzed crash data and skid resistance at five urban signalized intersections in Isparta, Turkey, finding that higher skid resistance and greater texture depth were associated with a lower probability of accidents [92].

Though these studies do not specifically focus on red-light running, they collectively underscore the importance of pavement friction and surface conditions in enhancing traffic safety at signalized intersections. Since red-light running is directly related to drivers' stopping behavior, enhancing pavement friction has significant potential to reduce red-light running crashes. Especially, intersections on high-speed arterials can particularly benefit from the deployment of such a system as drivers on these roads require a longer stopping distance to come to a

safe stop.

4.3. Improving Signal Timing Parameters

4.3.1. Adjusting Yellow Interval Length

The duration of the yellow interval is a crucial signal timing parameter in mitigating red-light running, as it directly influences drivers' decision-making when approaching an intersection during the transition from yellow to red. A shorter yellow interval may not provide drivers with sufficient time to safely come to a stop, whereas the effectiveness of a longer yellow interval may diminish over time. Extensive research has been conducted to understand driver's behavior during the yellow interval and the impact of its duration on intersection safety. In practice yellow intervals are typically calculated according to established guidelines [93] [94].

Olson and Rothery (1961) analyzed driver behavior at five signalized intersections in response to varying yellow intervals [95]. The findings indicate that driver behavior does not significantly change with different yellow intervals, as drivers are unaware of its duration. The study also reported that shorter yellow intervals result in longer dilemma zones, while longer yellow intervals shorten the dilemma zone, thereby improving stopping behavior. The authors recommended setting the yellow interval based on driver behavior and the size of the dilemma zone. Stimpson *et al.* (1980) conducted an observational before-and-after study at two intersections, where the yellow interval was increased from 4.7 seconds to 6 seconds and from 4.3 seconds to 5.6 seconds [96]. The study found that even small increases in the yellow interval could significantly reduce potential intersection conflicts. Zador *et al.* (1985) analyzed traffic data from 91 signalized intersections across the United States, concluding that intersections with adequately timed yellow intervals experienced significantly fewer rear-end and right-angle crashes compared to those with insufficient yellow timing [97]. Wortman *et al.* (1985) conducted a before-and-after study at two signalized intersections and their findings further supported that increasing the yellow interval from 3 seconds to 4 seconds significantly reduced the number of vehicles entering the intersection during the red phase [98]. The study also reported that extending the yellow interval was more effective than officer enforcement in reducing violations. Similarly, Horst (1988) conducted a one-year before-and-after study in the Netherlands, finding that a 1-second increase in the yellow interval led to a 50% reduction in red light running. However, yellow intervals exceeding 5 seconds showed negative effects [99]. Retting and Greene (1997) observed reductions in red-light running and the likelihood of rear-end crashes after implementing longer yellow intervals at 10 urban intersections to meet ITE standards [100]. Although the authors admitted that the effectiveness of this longer yellow interval may diminish over time. Bonneson *et al.* (2003, 2004, 2006) also reported longer yellow intervals to be very effective in reducing red-light running at high-crash intersections [23] [101] [102]. Retting *et al.* (2008) in their before-and-after analysis of red-light running

behavior found that increasing the yellow interval by 1 second resulted in a 36% reduction in the frequency of red-light running [103].

Overall, it is essential to ensure that yellow intervals are implemented according to appropriate guidelines, as shorter intervals can significantly increase the risk of red-light-running. As longer yellow intervals have been shown to improve RLR safety, a moderate increase in yellow interval length beyond recommendations of general guidelines can enhance safety at high-risk intersections. However, a substantial increase in yellow interval duration may lose its effectiveness over time, as frequent drivers could adapt their behavior upon perceiving the extended interval, potentially diminishing the intended safety benefits.

4.3.2. Adjusting Signal Cycle Length at Pretimed Signals

Cycle length is an important factor that, if not set correctly, can significantly affect performance and safety at signalized intersections. Shorter cycle lengths result in more frequent red intervals, which may increase the chance of red-light running. Conversely, longer cycle lengths can lead to driver frustration due to excessive delays, also affecting red-light running behavior. Therefore, cycle length should be properly optimized following established guidelines to balance these factors effectively. Few studies have examined the relationship between the length of the cycle length and red-light running behavior.

Chen *et al.* (2017) analyzed 12 months of high-resolution signal controller event data from five intersections in Minneapolis, MN, finding that longer cycle lengths are correlated with an increased number of red-light running [104]. The authors suggested that drivers may associate longer cycle lengths with excessive delays, leading to a higher likelihood of violations. However, the study noted a potential limitation due to insufficient sample sizes for different cycle lengths, which could introduce bias into the findings. However, Bonneson and Son (2003) used a probabilistic red-light-running prediction model and found that an increase in cycle length was associated with a reduction in red-light running [102].

Signal cycle length should be carefully optimized based on the time of day, following standard guidelines for signalized intersections, as both excessively short and long cycle lengths can negatively impact red-light running safety.

4.3.3. Providing or Adjusting All-Red Interval

The purpose of the all-red clearance interval is to provide extra time for red-light runners to clear the intersection before the conflicting movement receives the green signal. The primary focus of all-red clearance intervals is not to reduce RLR violations but to mitigate the crash risks associated with them.

Research on all-red clearance intervals at signalized intersections has shown varying impacts on red-light running safety. An FHWA case study evaluated the implementation of all-red interval (1.0 - 2.0 seconds) and an increase in signal head size (from 8 inches to 12 inches) at 33 signalized intersections in Detroit and Highland Park, Michigan [105]. The before-and-after crash count revealed significant safety improvements: angle crashes decreased by 75.7%, injury crashes by

45.5%, and total crashes by 33.3%. However, Souleyrette *et al.* (2004) found no long-term safety benefits with the implementation of the all-red interval, though a short-term improvement was noted [24]. Schattler *et al.* (2003) evaluated three intersections in Oakland County, Michigan where yellow and all-red intervals were updated according to ITE guidelines [106]. However, no conclusive differences in red-light running were found, though a significant decrease in late exits (exiting intersection after conflicting phase receives green interval) was observed. Retting *et al.* (2002) also evaluated intersections where existing yellow and all-red intervals were updated to meet ITE guidelines and reported an 8% reduction in total crashes, a 12% reduction in injury crashes, and a 37% reduction in pedestrian and bicyclist crashes [94]. In an earlier study Retting and Greene (1997) implemented yellow intervals, all-red intervals, or both at multiple locations and found no evidence of driver habituation to the all-red interval [107].

Most studies indicate that while the all-red interval does not reduce the number of red-light running, it does decrease its associated crash risk by reducing the number of late exits. Due to the safety cushion it provides, implementing all-red intervals at signalized intersections has become a common practice in the United States. Signal timing manuals by local, state, and federal governments provide guidelines on the duration of the all-red intervals; however, slightly longer intervals than those recommended guidelines can be used based on engineering judgement for high risk signalized intersections.

4.4. Removing the Need to Stop

Intersections are often considered the most hazardous sections of roadways due to the frequent stop-and-go activities of vehicles. This constant acceleration and deceleration not only challenges drivers but also puts them in a dilemma when deciding whether to proceed or stop at yellow lights. Minimizing the number of signal stops during a journey can help lower the risk of red-light running crashes.

4.4.1. Signal Coordination

Signal coordination, also known as traffic signal synchronization, is a traffic management strategy that aligns the timing of traffic signals along an arterial road to create a smooth flow of traffic, thereby reducing vehicles' travel time [54]. Although the primary goal of providing signal coordination is to facilitate vehicles traveling through multiple intersections without stopping, it can potentially decrease the occurrence of red-light running by reducing the need to stop at red light.

Several studies have analyzed the impact of signal coordination on traffic safety across different urban arterials. Yue *et al.* (2022) conducted a simulation study on three urban arterials in Reno, Nevada, finding that signal coordination reduced vehicular conflicts compared to non-coordinated operations, though this result can vary based on traffic volume [108]. Zhang *et al.* (2019) performed an empirical analysis using eleven years of data from six coordinated arterials in Ann Arbor, Michigan, revealing that while signal coordination reduced possible injury crashes

(C), it led to an increase in severe injury crashes (A and B), likely due to increased vehicle speeds from smoother operations [109]. In a separate study, Zhang *et al.* (2018) analyzed four years of pre and post-implementation data of coordinated signalized intersections located in the same city using regression modeling and found that crashes became more spatially dispersed with a 78% reduction in multi-vehicle crashes but rear-end and side-swipe crashes increased by 11.3% and 35.6%, respectively [110]. The authors also noted improved safety on arterials with higher speed limits, though peak-hour safety benefits under saturated conditions did not show significant improvement. Williamson *et al.* (2018) conducted a before-and-after crash analysis on five treatment corridors with signal coordination in Illinois, showing a 21% decrease in total crashes, a 52% reduction in injury crashes, and a 21% decrease in property damage-only crashes [111]. Li and Tarko (2011) examined short-term crash likelihood on three coordinated arterials in Indiana, finding that vehicles arriving in the second half of the green phase had a significantly lower likelihood of crashes, and so did arterials with short distances between intersections [26]. Additionally, in their study, arterials with coordinated signals and separate right-turn lanes showed greater potential in reducing rear-end and right-turn crashes.

Although the primary objective of signal coordination is to enhance operational efficiency, research has also shown its effectiveness in improving intersection safety. By reducing the number of stops and minimizing driver frustration, coordinated signals can enhance red light running safety on arterials with closely spaced intersections.

4.4.2. Removing Unwarranted Traffic Signals

Traffic signals are typically installed at intersections that satisfy specific criteria, such as the signal warrants established in the *Manual on Uniform Traffic Control Devices* (MUTCD) in the United States [112]. However, in areas experiencing population decline, some traffic signals may no longer meet these criteria, even though they were warranted at the time of installation. These unwarranted signals can lead to unnecessary delays and potential safety issues. Therefore, removing such signals can enhance both the operational efficiency and safety of the intersection. Few studies have examined the effects of installing and removing unwarranted traffic signals.

Agent and Green (2008) analyzed before-and-after crash data and found that installing unwarranted traffic signals led to a 28.3% increase in total crashes, primarily due to a 222% rise in rear-end crashes [27]. However, removing unwarranted signals resulted in a 40.2% reduction in angular crashes without creating additional safety concerns. Installing signals based on crash warrants led to a 42.9% reduction in total crashes. Persaud *et al.* (1997) conducted an Empirical Bayes (EB) before-and-after analysis of 199 treatment intersections and 71 comparison intersections in Philadelphia [113]. Their findings indicate that replacing unwarranted traffic signals with two-way stop signs on one-way streets reduced total crashes by 24%.

Due to the dynamic nature of urban growth, traffic demand, or commuter patterns, population distribution and travel route choices change over time. Therefore, it is essential to continuously evaluate whether an intersection still warrants signalization. Maintaining signals at intersections that no longer meet the criteria can lead to unnecessary delays and driver frustration, potentially increasing the likelihood of red-light running crashes.

4.4.3. Replacing Signalized Intersection with Roundabout

A roundabout is a circular intersection known for its safety and operational advantages. Roundabouts can minimize vehicle delays, by reducing the need for drivers to stop at red light [114]. Most of the research on intersection conversions to roundabouts has focused on transforming unsignalized intersections. However, a limited number of studies have examined the safety impacts of converting signalized intersections to roundabouts and showed that the safety benefits observed in the conversion of unsignalized intersections can also be replicated to signalized intersections. **Figure 7** shows an example of a signalized intersection converted into a roundabout.

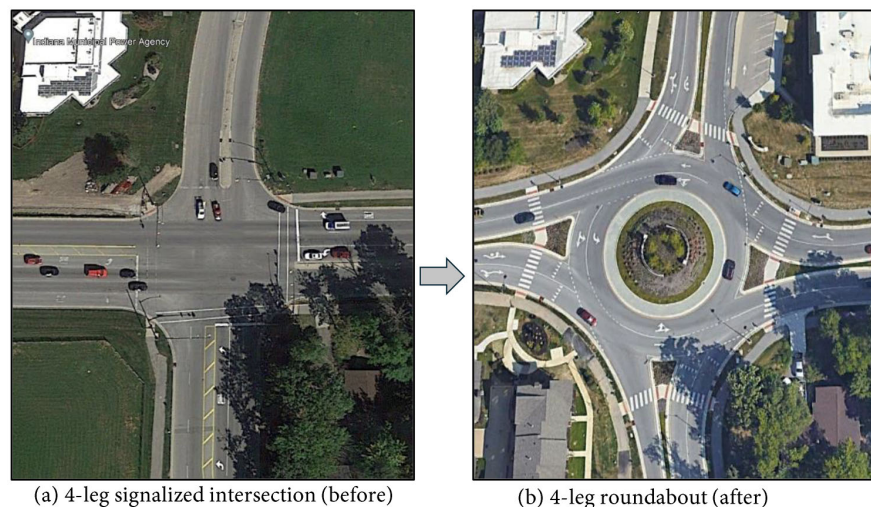


Figure 7. A signalized intersection converted to a roundabout at 116th Street & College Avenue in Carmel, Indiana (Image source: Google Earth).

Gross *et al.* (2013) analyzed the safety benefits of converting signalized intersections to roundabouts using the empirical Bayes (EB) method, evaluating 28 such conversions across various states in the United States [115]. The study found a 20.8% reduction in total crashes and a 65.8% reduction in injury crashes. However, the safety benefit for total crashes decreased with increasing traffic volumes, while the safety benefit for injury crashes remained consistent across all traffic volumes. Additionally, the analysis revealed considerable variation in crash reduction across the study sites. Jensen (2013) conducted an empirical Bayes (EB) before-and-after analysis on 332 converted sites in Denmark, which included both signalized and unsignalized intersections converted to roundabouts [25]. The

study found a greater reduction in the number of crashes for both signalized and unsignalized intersection conversions when the speed limit on roundabout arms was higher. However, the study also identified a negative impact on cyclist safety following these conversions. Persaud *et al.* (2001) analyzed the conversion of 23 intersections to roundabouts, including four signalized intersections. The study reported a 35% reduction in total crashes and a 74% reduction in injury crashes for four signalized intersections converted to roundabouts [116].

4.5. Dilemma Zone Protection with Signal Control Strategies

When drivers see the yellow light while approaching signalized intersections, they often face a dilemma about whether to stop or proceed. The area on the intersection approach where drivers face this dilemma during the yellow interval is called the dilemma zone. For vehicles caught in dilemma zone, an abrupt stop increases the likelihood of rear-end crashes, while speeding to clear the intersection increases the likelihood of red-light running and right-angle crashes [117]-[120]. Researchers have studied this issue over decades to understand driver behavior within the dilemma zone and to protect road users from its safety risk. Over the years, various techniques and systems have been developed and assessed to protect vehicles trapped in the dilemma zone and reduce the risk of red-light running. Most studies have focused on green or all-red extension/termination systems using different detection technologies, strategies, and controller settings. Advanced techniques are continuously being developed to enhance the accuracy and effectiveness of dilemma zone protection. **Figure 8** shows dilemma zone protection concepts with continuous wide-area radar sensor technology.

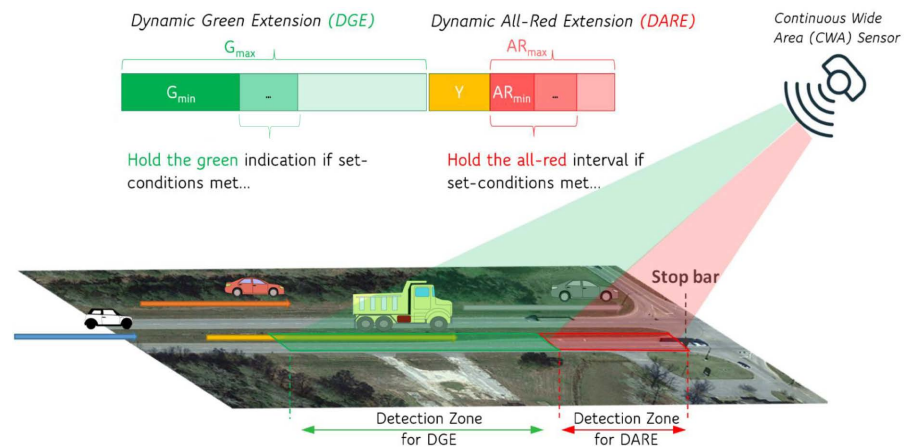


Figure 8. Dilemma zone protection concept with continuous wide area (CWA) detection.

In an early study, Webster and Ellson (1965) introduced a speed-based multi-detector system to mitigate the dilemma zone at high-speed intersections. Their study suggested placing a speed-sensitive detector 500 ft upstream of the stop line and a standard detector 130 feet from the stop line. Where the upstream speed-sensitive detector was designated solely for extending green signals for fast-mov-

ing vehicles enabling green extension for vehicles trapped in the dilemma zone [121]. In another early study on the dilemma zone, Zegeer (1977) conducted a before-and-after crash analysis on three signalized intersections in Kentucky following the implementation of a green extension system (GES) equipped with multiple loop detectors [122]. The study observed a 54% reduction in total crashes and a 75% reduction in rear-end crashes. Agent and Pigman (1994) assessed intersection approaches with GES, with Advance Warning Flashers (AWF), or without either system [57]. Their analysis, based on traffic conflict data revealed that the GES was more effective than both AWF and the absence of any system in addressing the dilemma zone issue at high-speed signalized intersections. Bonneson *et al.* (2002) evaluated the detection-control system (D-CS) at two signalized intersections in Texas [123]. The system effectively reduced the number of vehicles caught in the dilemma zone, decreased overall delay, and accurately detected the presence of trucks preventing them from being trapped in the dilemma zone. Zimmerman and Bonneson (2005) further analyzed the D-CS system using crash and traffic data from five signalized intersections in Texas, finding a 58% reduction in RLR violations, an 80% reduction in heavy vehicle violations, and a 39% reduction in severe crashes [124]. Tarko *et al.* (2006) utilized a probabilistic method to optimize green extension timing, aiming to minimize the likelihood of vehicles present in the dilemma zone. Their simulation-based investigation at two high-speed intersections showed that this method can successfully lower the frequency of vehicles trapped in the dilemma zone [125]. Zimmerman (2007) conducted a simulation study to assess the impact of providing additional green extension time for trucks caught in the dilemma zone [126]. The study result showed fewer trucks being caught in the dilemma zone without negatively affecting intersection efficiency. Zhang *et al.* (2011) proposed a probabilistic model to predict red light running hazards by analyzing factors like speed, distance, and car-following behavior for a Dynamic All-Red Extension (DARE) system [127]. The system achieves over 65% to 90% correct detection rates with a 5% false alarm rate, showing effective red-light running hazard detection.

Olson (2012) performed a before-and-after crash analysis on loop detector-based all-red extension system using the EB method and a simulation study at eight signalized intersections in Portland, Oregon [128]. The study reported a reduction in right-angle crashes with crash modification factors (CMF) ranging from 0.36 to 0.92. Wang *et al.* (2012) developed an algorithm to predict red-light runners for a multi-loop detection system and evaluated its performance with data from video sensors [129]. The authors concluded that reasonable predictions could be achieved using a two-loop detector system, assuming constant vehicle speed and car-following status. Chang *et al.* (2013) evaluated a dilemma zone protection (DZP) system with a dynamic all-red extension (DARE) feature using radar sensors at an intersection in Maryland [29]. The system successfully detected red-light runners and extended the all-red interval without any false alarms (Incorrect identification of red-light runners). Later, Park *et al.* (2016) simulated the

effectiveness of a variable message sign (VMS) combined with the DARE feature, achieving 100% protection for red-light running vehicles with minimal false alarms [130]. Hurwitz *et al.* (2016) compared two different all-red extension techniques i) downstream detection (DD) and ii) smart upstream speed-conditional detection (SUSCD) using loop detectors in a simulation study [131]. The study found that the DD system performed better in identifying high-risk vehicles and providing appropriate extensions with less delay, while the SUSCD system showed better efficiency. Zha *et al.* (2016) conducted a simulation study on an all-red extension system with advanced warning under vehicle-to-infrastructure communications, finding that at full market penetration, the proposed model offered a great dilemma zone protection with reduced delays for conflicting movements [132]. However, at a 40% penetration level, its performance was similar to that of a typical green extension system. Gates and Noyce (2016) developed a conceptual framework for all-red extension systems and evaluated their performance through vehicular event data modeling [133]. The study demonstrated that using a higher deceleration rate as a threshold value could accurately classify red-light runners, while minimizing false alarms. Abbas *et al.* (2017) compared different dilemma zone protection technologies, including DCS, multi-loop, and radar sensor-based green extension systems, using simulation [134]. The radar sensor-based system outperformed others, with an 80% reduction in red-light running, particularly when sight distance was not an issue.

Simpson *et al.* (2017) conducted a long-term operational, safety, and driver behavior study in North Carolina on an all-red extension system using multiple loop detectors [135]. The study found no statistically significant difference in red-light running frequency after 12 months, suggesting that drivers did not adapt to the all-red extension system, and the operational performance was minimally impacted by false activation. In a subsequent study, Simpson (2023) conducted a before-and-after EB analysis of 16 signalized intersections in North Carolina, equipped with the same all-red extension system [136]. The study observed a 7% reduction in RLR crashes at all treatment sites and a significant 35% decrease in such crashes at multilane-to-two-lane intersections. Park *et al.* (2018) field-tested a DZP system with a DARE feature achieved by radar sensor at two high-speed signalized intersections in Maryland [137]. The study showed that the DZP system with wide-area radar detection can effectively detect red-light runners and extend the all-red interval accordingly. A reduction in the length of the dilemma zone was also observed after the system implementation. Zhao *et al.* (2023) conducted a simulation study on a trajectory optimization-based dilemma zone protection using connected vehicle technology, finding a significant reduction in the number of vehicles caught in the dilemma zone [138].

Recently, Rahman *et al.* (2023) analyzed high-resolution signal event data along with detector log data to evaluate the effectiveness of radar sensor-based DZP system deployed at seven signalized intersections on high-speed, multi-lane, rural arterials in Alabama [30]. The study found that the DZP-treated intersections

have shown significant improvement in both safety and operations with about a 65% increase in vehicle arrival on the green, a 50% reduction in RLR violations, a 71% reduction in abrupt stops, a shift of the dilemma zone closer to the intersection stop line, and a significant reduction of its length. Chen *et al.* (2023) evaluated an integrated intelligent intersection control system (III-CS) at a signalized intersection in Maryland [139]. The system offers a risk-based gap-out operation utilizing dynamic green and all-red extension features with a radar sensor. The system achieved 100% detection of red-light-running vehicles with a false alarm rate between 7.3% and 11.7%. It also reduced the number of vehicles trapped in the dilemma zone by 17.9% to 18.5%.

The dilemma zone protection system with advanced detection technology is one of the most sophisticated methods currently available for improving red-light running safety. Both the green and all-red extension features of the dilemma zone protection system have demonstrated significant improvements in safety at high-speed signalized intersections. However, its complexity and associated costs are relatively higher than other available countermeasures.

5. Possible Future Research Trends in Preventing Red-Light Running

Future research trends and techniques in preventing red-light running in future will increasingly focus on the integration of Artificial Intelligence (AI) and Connected and Automated Vehicle (CAV) technologies. AI-driven predictive modeling has already gained prominence in traffic crash analysis, risk assessment, and identification of critical crash parameters and high-risk locations facilitating more targeted safety interventions. The further application of AI in traffic systems holds immense potential for future advancements. Li *et al.* (2014) used vehicle trajectory data within an artificial neural network (ANN) framework, achieving an 80% accuracy rate in identifying potential red-light runners [140]. Such integration of AI-based real-time red-light running prediction combined with the DARE system has the potential to significantly enhance red-light running safety. Furthermore, AI-driven adaptive traffic signal control systems (ATSC) have also shown potential by leveraging real-time traffic flow data, weather conditions, conflict detection, and other variables to optimize signal operations while simultaneously improving intersection safety [141].

CAV technology also holds significant promise in mitigating red-light running through vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication. Hadi *et al.* (2021) evaluated the safety benefits of a Red-Light Violation Warning (RLVW) in a simulation-based connected vehicle environment, demonstrating that, RLVW could enhance intersection safety by approximately 50.7%, particularly in reducing rear-end and right-angle conflicts under a 100% CAV adoption scenario [142]. Additionally, Li *et al.* (2014) illustrated that real-time traffic signal timing and vehicle trajectory data, which can be efficiently gathered through V2V and V2I communication, can be utilized to enhance the perfor-

mance of DARE systems [143]. Incorporating such trajectory data from a connected vehicle environment has the potential to improve the detection accuracy of red-light runners while reducing false alarm rates of DARE systems.

While most CAV-based research remains confined to simulation studies, as these technologies continue to develop and become more widely implemented, they are likely to play a critical role in enhancing red-light running safety.

6. Conclusions

This review paper aims to provide an in-depth analysis of engineering countermeasures intended to mitigate red-light running and its associated crash risk. Through a systematic literature review, it synthesized research findings on various countermeasures developed and tested globally. The analysis revealed significant variability in the effectiveness of these countermeasures, which can be attributed to contextual factors such as geography, traffic dynamics, geometric design, driver behavior, and other site-specific variables.

Signal visibility enhancements, such as signal backplates with retroreflective borders and larger signal heads have generally been reported to improve safety by making traffic signals more visible and conspicuous to drivers. However, their effectiveness can vary significantly, especially depending on the severity of visibility issues the intersection had prior to the improvements.

Countermeasures to improve the driver's awareness and likelihood of stopping, such as pavement markings, advance warning flashers (AWFs), traffic signal countdown timers (TSCT), flashing signals, in-vehicle alerts, and pavement surface conditions also shown positive results with some drawbacks. Thus, while these measures can enhance driver awareness and reduce RLR crashes, their success may also depend on proper site selection, implementation, and other contextual factors. For example, studies on AWFs, flashing signals, and traffic signal countdown timers (TSCT) showed mixed results, with some studies indicating a reduction in red light running while others showing an increase in violations or rear-end crashes. Therefore, post-implementation monitoring is necessary to ensure that the desired safety performance is achieved. Enhancements in pavement surface friction and the use of transverse rumble strips have the potential to improve stopping behavior, though more research is needed to conclusively measure their impact specifically on red-light running at signalized intersections.

Adjustments to traffic signal timing parameters, such as cycle length, yellow interval, and all-red interval, can significantly impact intersection safety. However, these changes must be implemented according to proper guidelines to be effective otherwise too long or too short implementation of these measures can have negative consequences on intersection safety. Traffic signal coordination, removal of unwarranted traffic signals, and the construction of roundabouts can also be highly effective engineering countermeasures for red-light running, provided they are warranted by guidelines.

The most effective countermeasures preventing red-light running crashes cur-

rently are dilemma zone protection (DZP) systems with advanced detection technologies. Dilemma zone protection systems can effectively reduce the number of vehicles trapped in the dilemma zone, thereby decreasing the potential for red-light running. Furthermore, the inclusion of an all-red extension feature, which provides additional clearance time for red-light running vehicles to safely clear the intersection, further enhances intersection safety. With advancements in vehicle detection technologies, the performance of the DZP system continues to improve, highlighting its future potential. However, the implementation of advanced dilemma zone protection systems can be complex and costly, which may limit their widespread application.

Overall, this review underscores the importance of evaluating the unique characteristics of intersections, and red-light running behavior to select targeted safety countermeasures for achieving sustainable safety improvements. The selection of the best possible countermeasures may also vary depending on region-specific factors, including geographical context, traffic characteristics, available expertise and resources, etc. While extensive research exists on red-light running countermeasures, this paper reveals that some countermeasures still lack enough scientific studies to draw definitive conclusions about their effectiveness. By providing a comprehensive overview of existing research, this review paper can help future researchers identify gaps and potential areas for further investigation, ultimately contributing to the advancement of red-light running safety research.

Limitations

This review primarily examines the safety performance of red-light running countermeasures. Consequently, studies focusing on operational performance may not be included. Also, many relevant studies from various regions of the world were either not published in English or were not included in indexed journals. Consequently, these non-English and non-indexed publications were not included in the review. Despite a thorough literature search to identify articles on engineering countermeasures for red-light running, the authors recognize that some relevant studies may have been unintentionally missed.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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