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MINETA TRANSPORTATION INSTITUTE

Right Turn on Red: Energy-Saving Measure or Unsafe Maneuver?

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MINETA TRANSPORTATION INSTITUTE

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16. Abstract
There is a growing interest in prohibiting right turn on red (RTOR) policies in the name of pedestrian and bicycle safety but there is not enough research on the subject to help agencies make informed decisions. When Congress passed the Energy Policy and Conservation Act of 1975, they included a provision requiring states to permit right turns on red lights as an energy-saving measure to receive federal assistance for mandated conservation programs. Since 1980, all states have permitted right turns on red as a general rule. More research is needed to help guide state policies that can support jurisdictions in making more informed and context-sensitive decisions. This research examines the infrastructure design and built environment-related factors associated with RTOR collisions—particularly those involving pedestrians and bicyclists. We also looked at emissions issues for RTOR maneuvers. Our findings reveal that RTOR movements are generally unsafe for pedestrians, bicyclists, and drivers, while only marginally useful in lowering emissions and only under certain contexts. Those marginal benefits may further decline with increased electric vehicle (EV) adoption. Despite RTOR crashes being a small portion of collisions and fatalities at signalized intersections, they tend to be more severe for vulnerable road users (e.g., bicyclists and pedestrians). Additionally, given the rise of SUVs/pickups in the U.S. personal automobile fleet—which tend to cause more severe collisions—RTOR prohibition is a proactive safety strategy consistent with the internationally recognized and USDOT-adopted Safe Systems approach. We recommend that state policy should make it easier for California communities to prohibit RTOR movements. We also recognize that banning or permitting RTOR movements should acknowledge the specific contexts of the communities (their place types), which could unduly burden cities that want to allow or prohibit RTOR at a vast number of their intersections in terms of signage. Informed decisions about RTOR policies can improve road safety for all.

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Background

There is a growing interest in removing right turn on red (RTOR) policies in the name of pedestrian and bicycle safety, but there is a serious lack of research on the subject that can help agencies make an informed decision. When Congress passed the Energy Policy and Conservation Act of 1975, they included a provision requiring states to permit right turns on red lights as an energy-saving measure to receive federal assistance for mandated conservation programs. Since 1980, all states have permitted right turns on red as a general rule, but few studies have looked at pedestrian and bicyclist injuries at intersections with a focus on the potential danger of right turns on red, therefore more research is needed to help jurisdictions make more informed decisions.

Objectives and Methods

This research set out to understand infrastructure design and built environment-related factors associated with RTOR crashes, in particular those involving pedestrians and bicyclists. We reviewed RTOR collisions throughout the state and explored issues around emissions for RTOR maneuvers.

During our review of RTOR collisions, we revealed that a higher proportion of RTOR collisions were occurring in low socioeconomic status (SES) areas, which led us to conduct a deeper set of analyses using linear regression models and a host of built environment, collision, and socioeconomic status variables. Additionally, we conducted a case study in the City of Los Angeles to identify and analyze intersections where high numbers of RTOR collisions were occurring.

Results

In our exploratory analysis, we found that right-turn collisions at signalized intersections were responsible for over 39,000 collisions and 217 fatalities (involving pedestrians, bicyclists, and drivers) between 2011 and 2022 in the state of California. Over half of these collisions involved a pedestrian or a cyclist. Our crash data analysis and the existing literature lead us to conclude that RTOR movements are generally unsafe for pedestrians, bicyclists, and drivers and hinder the livability of streets for vulnerable road users.

RTOR movements are only marginally useful in lowering emissions and only in certain contexts. Those marginal benefits have declined over the years as internal combustion engine vehicle (ICEV) technology has improved and may further decline with increased electric vehicle adoption. Our model of RTOR collisions, SES status, and race revealed key insights into factors influencing collisions at intersections. Variations by mode of travel are notable; for instance, race impacts pedestrian but not cyclist collision odds, with Black pedestrians facing increased risk of failures to yield incidents. Neighborhood socioeconomic status (SES) also plays a crucial role: higher SES reduces the odds of pedestrian failures to yield collisions but paradoxically increases right-turn collision odds. SES decreases the odds of cyclist right-turn collisions but shows no effect on failures to yield. These findings underscore the nuanced relationship between SES and collision dynamics.

In our case study analysis, we found several common characteristics for intersections with the highest numbers of right-turn collisions for pedestrians and cyclists. Most of these intersections were located near transit stops—likely resulting in a higher volume of pedestrians. We also found that these intersections were in commercial areas with large parking lots, as well as relatively heavy, fast-moving cross traffic. Additionally, several intersections had irregular designs that could add to confusion or distraction among drivers.

Conclusions

We found that RTOR movements are generally unsafe for pedestrians, bicyclists, and drivers, while only marginally useful in lowering vehicle emissions and only in certain contexts. In sum, we generally recommend prohibiting RTOR movements. We recognize, however, that the decision to ban or permit RTOR movements should take into account the specific contexts of the cities (their place types), which could unduly burden cities that want to permit or prohibit RTOR at a vast number of intersections in terms of signage. Therefore, we recommend that cities be able to determine whether they want to ban RTOR movements citywide and then sign intersections according to whether such movements are permitted or prohibited based on the specific contextual factors of the types of places and intersections they have and the type of city they want to be.

1. Introduction

The Energy Policy and Conservation Act of 1975 included a provision requiring states to permit right turns on red (RTOR) as an energy-saving measure to receive federal assistance for mandated conservation programs (Zador et al., 1982). Following the legislation, by 1980, all states had permitted RTOR as a general rule unless otherwise prohibited at specific intersections based on guidance available from sources such as federal and state versions of the Manual on Uniform Traffic Control Devices (MUTCD) and design manuals. The relevant guidance in the MUTCD Section 2B.54 specifies several conditions *that may be used* to prohibit RTOR at signalized intersections (Federal Highway Administration, 2009). The state laws applicable in most jurisdictions of the United States require RTOR to remain legal at intersections unless a sign specifically prohibiting the maneuver is posted.

Prohibition of RTOR at specific intersections is often in response to high pedestrian crashes and/or pedestrian activities. Therefore, in most communities, the decision to prohibit RTOR is governed by a *reactive* approach, applied on a case-by-case basis according to the aforementioned MUTCD section. New York City remains an exception, where RTOR is mostly prohibited except for some of the intersections on Staten Island (Lord, 2002; NYC311, 2024).

Given the current interest in active modes of travel and recent data showing pedestrian and bicyclist (Vulnerable Road Users or VRUs) fatalities in the US rising at a faster rate than automobile occupant fatalities, agencies have begun to look at measures that proactively protect VRUs rather than traditionally reactive hot-spot based approaches (Reish, 2021). Recently, Washington, D.C. banned right turns on red (effective 2025), joining New York City in an effort to protect pedestrians. Several cities in California, including Berkeley and San Francisco, are also considering a similar proposal (D.C. Law 24-214; Taplin, 2022; Olea, 2023). However, existing statewide policies in California may present a barrier to these communities trying to prohibit RTOR. For example, the San Francisco Metropolitan Transportation Agency (SFMTA) in their July 2023 memo cited the state law as a barrier to implementing a city-wide ban on RTOR (Olea, 2023): *"Under existing California law, turns on red would continue to remain legal unless signed, thereby any citywide approach would require the posting of signs at each of the approaches to San Francisco's over 1,300 traffic signals."*

Given this context, this study has the following objectives:

- To examine relevant evidence in collision data and literature to establish if RTOR prohibition is consistent with the Safe Systems approach.

- To examine the relevance and context-sensitivity of emissions reduction due to permitted RTOR given the current and expected future vehicle fleet.

- To provide potential state and local-level policy options and discuss their pros and cons given the nature of the evidence that can help communities in different states adopt context-sensitive RTOR policies.

2. Literature Review

2.1 Safety-Related Evidence

In a detailed investigation of the broader permitted RTOR policy's safety impacts, the National Highway Traffic Safety Administration (NHTSA) submitted a report to Congress in 1994 (Compton & Milton, 1994). The report looked at data from Illinois, Indiana, Maryland, and Missouri and found approximately 84 fatal crashes from 1982 to 1992 involving a right-turning vehicle at intersections where an RTOR is permitted. The report indicated that 44 percent of the crashes involved pedestrians and 10 percent involved bicyclists. In total, RTOR crashes at signalized intersection approaches represented .06 percent of the total number of fatal crashes in those four states. These numbers were consistent with the wider context of the safety issues prevalent in the automobile-oriented traffic environment at the time, and later studies tended to validate that. For example, Lord (2002) analyzed crash statistics in the US and Canada and concluded that the safety impacts of RTOR were minimal, citing the low speed of drivers who are performing the RTOR maneuver and a low proportion of pedestrian crashes. Fleck and Yee (2002) also argued that collisions due to the RTOR maneuver were low, even in the dense environment of San Francisco.

Zador's 1982 study found a "highly significant increase in right turn crashes at signalized intersections after adoption of RTOR" (p. 226). These increases were larger amongst pedestrians, particularly elderly pedestrians. Zador's 1984 literature review of RTOR studies also noted that "[a]llowing vehicles to turn right on red at signalized intersections increases all right turning crashes by about 23%, pedestrian crashes by about 60%, and bicyclist crashes by about 100%" (p. 245).

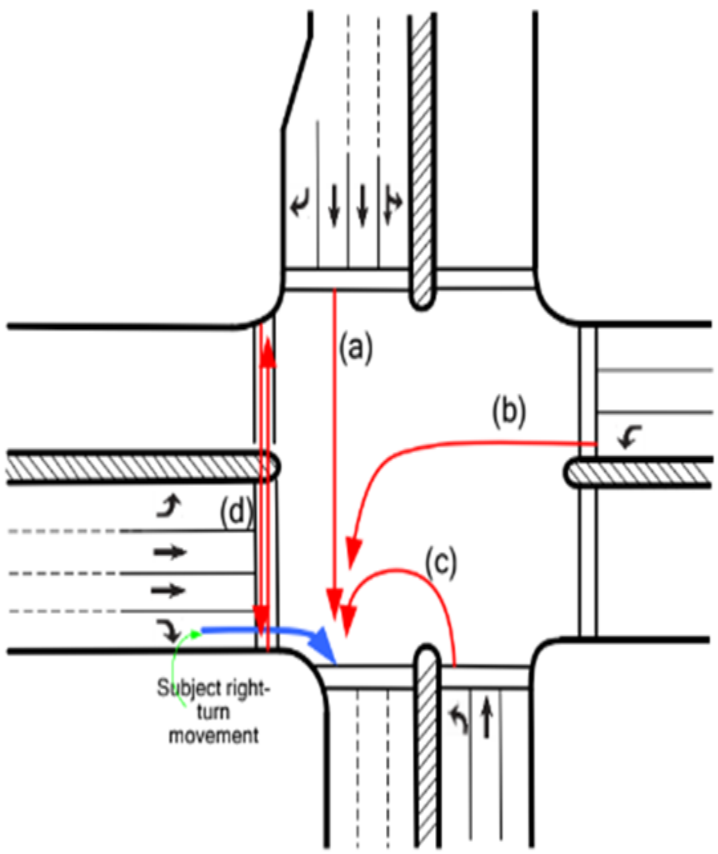
More recent studies have noted that banning RTOR can create a safer and friendlier road environment for VRUs. A study in Washington, D.C. by Wolfgram et al. (2022) found that intersections that had implemented a no-turn-on-red (NTOR) rule were safer for *both* pedestrians and drivers. Islam et al. (2022) conducted a statewide study in Utah and found that intersections that banned RTOR were safer than those that allowed it and had a decrease in expected pedestrian crashes by 37 percent. The City of Seattle reported a reduction in automobile-VRU conflicts after they made prohibiting RTOR at intersections the default setting at new or modified intersections. The city instituted this policy after a "top-to-bottom" review of its Vision Zero program (City of Seattle, 2023; Packer, 2023).

2.2 Factors Associated with RTOR Crashes

Previous studies have also explored major factors leading to RTOR collisions. One report categorized RTOR collisions into four conflicts: "a) Cross-street through movement, b) Opposing left-turn movement, c) Cross-street U-turns, and d) Cross-street pedestrians." These collision typologies are demonstrated in Figure 1 (Yi et al., 2012). A significant factor for these collisions is that drivers often do not follow existing RTOR laws, which require that drivers come to a complete stop at the limit line on a red light before making a right turn. A study by the Connecticut DOT noted that NTOR could help pedestrians feel more comfortable crossing the street if they feel confident that drivers will comply with RTOR restrictions (Connecticut DOT, 2024). However, most drivers do not come to a complete stop and instead roll through the limit line, creating a safety hazard specifically to pedestrians in the crosswalk. For example, one Florida study found that 70 percent of drivers did not stop at the limit line before starting their turn (Yan et al., 2008). Another major factor is that drivers are often looking left for oncoming traffic while making right turns and do not look out for pedestrians in the crosswalk on their right (Wu et al., 2017; Listgarten 2022) (see Figure 2).

To address conflicts between right-turning automobile traffic and other road users, partial prohibition and other treatments have been considered. On individual intersections, signs prohibiting RTOR have been implemented based on the time of day and/or presence of pedestrians, but those have limited effectiveness due to compliance issues (Retting et al., 2002). Guo et al. (2020) found that a raised channelized island and acceleration lane on the cross-street lea to the lowest conflict rate, followed by a painted channelized island and an acceleration lane on the cross-street.

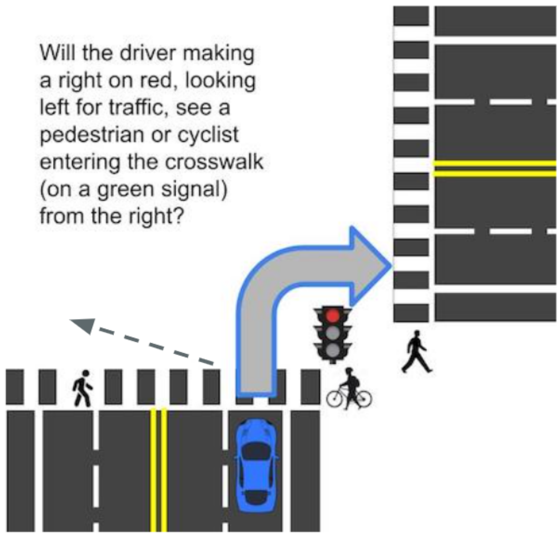
Figure 1. Movements Potentially Conflicting with RTOR Vehicles



Source: Yi et al., 2012

Protected intersections, which physically separate VRUs from automobiles, can also improve safety for cyclists. According to the National Association of City Transportation Officials (NACTO), protected intersections, "… can reduce the likelihood of high-speed vehicle turns, improve sightlines, and dramatically reduce the distance and time during which people on bikes are exposed to conflicts."

Figure 2. Illustration of Distracted Driver Looking Left for Oncoming Traffic Missing the Pedestrians or Bicyclists Crossing the Street



Source: Listgarten, 2022

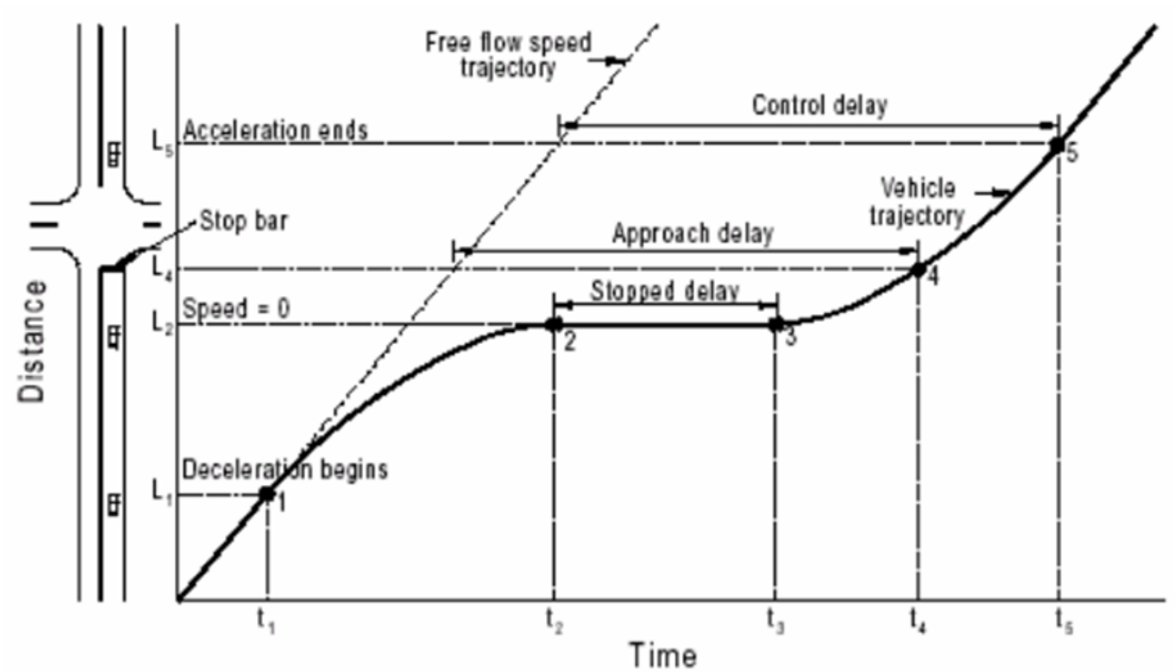
While safety literature's evidence on RTOR is mixed, it does point to the need to examine more recent crash statistics and reframe the issue in the context of the Safe Systems approach.

2.3 Studies on RTOR – Associated Emissions Reductions

As mentioned previously, the permissible RTOR maneuver was introduced in the 1970s as a fuel savings measure in response to the oil crisis. Given the state of technology of the internal combustion engine vehicles (ICEV) in that era, fuel savings are also translated into emissions reduction. This section provides more recent literature on the subject along with vehicle trajectories through individual four-way signalized intersections in a variety of contexts to critically examine if permitted RTOR still leads to similar emissions reduction.

Emissions from ICEVs are the predominant source of greenhouse gas emissions and other air pollutants of public health concern (Pandian et al., 2009). The predominant mode of vehicle activities in urban areas is a stop-and-go condition. In this mode, vehicles cruising at a speed need to decelerate toward the stop bar, spend idle time at a red light, and then accelerate to match the speed of the exiting traffic. Figure 3 shows the space-time trajectory of a vehicle moving through an intersection. The stopped delay component represents the amount of idle time spent at the intersection (the speed of the vehicle is zero during this time). In contrast, the control delay component combines the stopped delay with the delay occurring due to acceleration and deceleration of the vehicles (Darma et al., 2005).

Figure 3. Various Delay Components for Time Spent at Intersection



Source: Darma et al., 2005

Based on a synthesis of past research, including Darma et al. (2005), Pandian et al. (2009), and Lin et al. (2016), several factors determine the emissions by right-turning automobiles at signalized intersections. These factors are listed below and provide the context for where the fuel savings and emissions reductions by permitting RTOR may be significant.

- The intersection geometry:
    - The turning radius available to the right-turning vehicles
    - Visibility of conflicting traffic and pedestrians
    - Presence of markings and channelization
    - Presence of bulb-outs for pedestrian crossing
    - Bicycle lane treatment

    - Presence of on-street parking
- Intersection control configuration:
    - Protected or permitted movement of right turns
    - Presence of leading pedestrian intervals (LPI)
- Traffic composition:
    - Presence of slow-moving and medium/heavy-duty vehicles in the traffic stream
    - State of traffic:
        - The flow, density, and speed of traffic in the mainline and the conflicting street
        - The queue length
- VRU activity:
    - Number of pedestrians waiting and crossing
    - Number of bicyclists
    - Surrounding land-use
    - Enforcement of traffic laws

Rouphail et al. (2001) empirically studied the effect of intersection operations on the exhaust emissions of ICEVs. They found that the amount of exhaust emissions is not fully dependent on the amount of control delay. Rather, the emissions increase disproportionately during the acceleration episodes. A gradual increase in speed from an idle position will create fewer emissions than a vehicle stopping and accelerating multiple times to negotiate with conflicting traffic. Therefore, if drivers adhere to the provisions in the law that require them to stop at the red light, permissible RTOR movements may be more emissions-prone than approaches with RTOR prohibitions. It would especially be the case in highly conflicting environments (major urban centers) compared to signals with less conflicting traffic (suburban to rural environments). This is consistent with findings from a study by the Connecticut DOT which noted that the operational and emissions impact of RTOR restrictions vary widely from intersection to intersection (Connecticut DOT, 2024).

Increased adoption of electric vehicles (EVs) will further reduce emissions benefits even in more suburban environments since EVs reduce tailpipe emissions to zero. Given EVs' heavier composition and acceleration rates that are dramatically higher than ICEVs, increased EV adoption makes the case for prohibiting RTOR even stronger from a VRU-safety perspective. California's share of electric vehicle sales continues to increase year after year; with EVs making up almost 24 percent of all new vehicle sales in the last quarter of 2023 (California Energy Commission, 2024). This trend will continue to increase as the state moves toward its mandate of 100 percent of all new vehicles being EVs by 2035, as stipulated in Executive Order N-79-20.

2.4 Complementary Measures to Reduce RTOR Collisions

The Federal Highway Administration (FHWA) provides safety countermeasures for signalized intersections, including leading pedestrian intervals (LPI) that ought to complement RTOR prohibitions. For example, prohibiting RTOR may lead to increased right turns made in the green phase, and LPI may allow pedestrians to cross before a vehicle can turn. On individual intersections, signs prohibiting a right turn on red may be implemented based on the time of day and/or presence of pedestrians, but those have limited effectiveness due to compliance issues (Retting et al., 2002).

Guo et al. (2018) found that a raised channelized island and acceleration lane on the cross-street has the lowest conflict rate, followed by a painted channelized island and an acceleration lane on the cross-street. Protected intersections—which physically separate VRUs from automobiles—can also improve safety for cyclists. According to the National Association of City Transportation Officials (2020), "This design can reduce the likelihood of highspeed vehicle turns, improve sightlines, and dramatically reduce the distance and time during which people on bikes are exposed to conflicts."

2.5 Evaluations at the Micro Level

This discussion examines the literature on evaluating the impact of prohibiting or allowing the right turn on red at an individual intersection level. In contrast, the individual impacts are not the focus of this research. The research and relevant analysis are useful to agencies in implementing policies and creating outreach material while implementing policies prohibiting the right turn on red. The authors discuss both safety and emissions impact.

Safety Impact at Individual Intersections

The safety impact of modifications to individual roadway locations (segments and intersections) is quantified as a crash modification factor (CMF). A CMF is a multiplicative factor used to compute the expected number of crashes after implementing a given countermeasure at a specific site. CMFs specific to a variety of modifications may be found in the Highway Safety Manual Part D (American Association of State Transportation Officials, 2010). Ongoing research that has more recently estimated CMFs corresponding to various crash countermeasures may be found at the CMF clearinghouse, which provides CMF data and includes guidance on the use of CMFs.

According to the CMF clearinghouse, right-turn prohibition at urban intersections is reported (CMF Clearinghouse by FHWA) to have an overall CMF of 0.625 (representing a 37.5 percent reduction) for all crashes involving a right turn. For vehicle-pedestrian crashes involving right turns, the CMF is 0.709 (i.e., ~29 percent reduction following the prohibition). At locations with high pedestrian and bicyclist volumes, restricting RTOR can lead to a 50 percent reduction in crashes involving these VRUs. As noted by the Connectiut DOT, NTOR could also help pedestrians feel more comfortable crossing the street if they feel confident that drivers will comply with RTOR restrictions (Connecticut DOT, 2024).

3. Research and Analysis

3.1 Data Sources

Several data sources were used for this analysis. Data on bicycle, pedestrian, and vehicle collisions were obtained from the Statewide Integrated Traffic Records System (SWITRS), a California initiative that collects information from police reports on traffic collisions within the state. Using this data, we identified two dependent variables. Right-turn collisions were defined as any collision at an intersection that was immediately preceded by the vehicle attempting to make a right turn. yield violation collisions were identified as any collision immediately preceded by an illegal failure of the driver to yield, according to California Vehicle Code 21453, Section B, which states:

> Except when a sign is in place prohibiting a turn, a driver, after stopping as required by subdivision (a), facing a steady circular red signal, may turn right, or turn left from a one-way street onto a one-way street. A driver making that turn shall yield the right-of-way to pedestrians lawfully within an adjacent crosswalk and to any vehicle that has approached or is approaching so closely as to constitute an immediate hazard to the driver and shall continue to yield the right-of-way to that vehicle until the driver can proceed with reasonable safety.

SWITRS was also used to identify pertinent event-level predictors, including the race of the drivers and the pedestrian or cyclist, categorized as white (reference), Black, Hispanic, Asian, and other. One limitation of this measure is the inability to distinguish between Hispanic and non-Hispanic individuals within these racialized categories, which may affect the interpretation of our results. Additional predictors included whether the cyclist or pedestrian was male (1 = yes, 0 = no), their age, whether the driver was under the influence of a controlled substance, and whether the driver was driving at an unsafe speed. We also included several road condition measures from SWITRS, such as whether the collision occurred at night, whether the road was dry, and whether the weather was adverse.

We used the Caltrans Active Transportation Benefit-Cost Tool to identify other statewide road conditions. These included whether the road was a major arterial, the speed limit for bicycle models, the presence of bicycle infrastructure, and the estimated density of cyclists on that road on a typical day. We also included several larger census-tract level measures. Using data from the 2015–2019 American Community Survey, we identified neighborhood demographics, including the percentages of Black, Hispanic, and Asian residents. We assessed neighborhoods' socio-economic status (SES) using principal component analysis to derive an SES score from median rent, median home value, percent college educated, and median household income.

Next, we utilized a place typology that included seven categories: urban centers (reference), urban places, compact suburban places, suburban places, rural places, employment centers, and special districts. The place typology dataset was developed by Frost et al. (2018) and is described in the article, “Quantifying the Sustainability, Livability, and Equity Performance of Urban and Suburban Places in California.” The place typology was developed using a principal component analysis of six major variables: density, land mix, diversity, design, distance, and destination. The density variable included housing, population, and employment density. Land use mix refers to the employees per acre in different industries, such as entertainment and retail. Diversity encompassed both building diversity (including the percentage of renter-occupied units and multi-family housing) and regional diversity. The design variable focused on street design, including intersection density and walkability. The distance variable referred to transit accessibility, while the destination variable referred to job accessibility (Frost et al., 2018).

We also used walkability scores from the Environmental Protection Agency’s Smart Location Database (SLD), which calculates relative walkability by block group. According to the National Walkability Index Methodology (2021), relative walkability is determined by three main variables: intersection density, proximity to transit stops, and diversity of land uses.

3.2 Scope of Right Turn and Yield Collisions for Pedestrians, Cyclists, and Vehicles

As shown in Table 1, collisions and fatalities involving right turns at intersections and yield violations are much higher for vehicles compared to pedestrians and cyclists. However, fatalities were more common for pedestrians involved in right-turn-at-intersection collisions compared to drivers or passengers (**Table 1**).

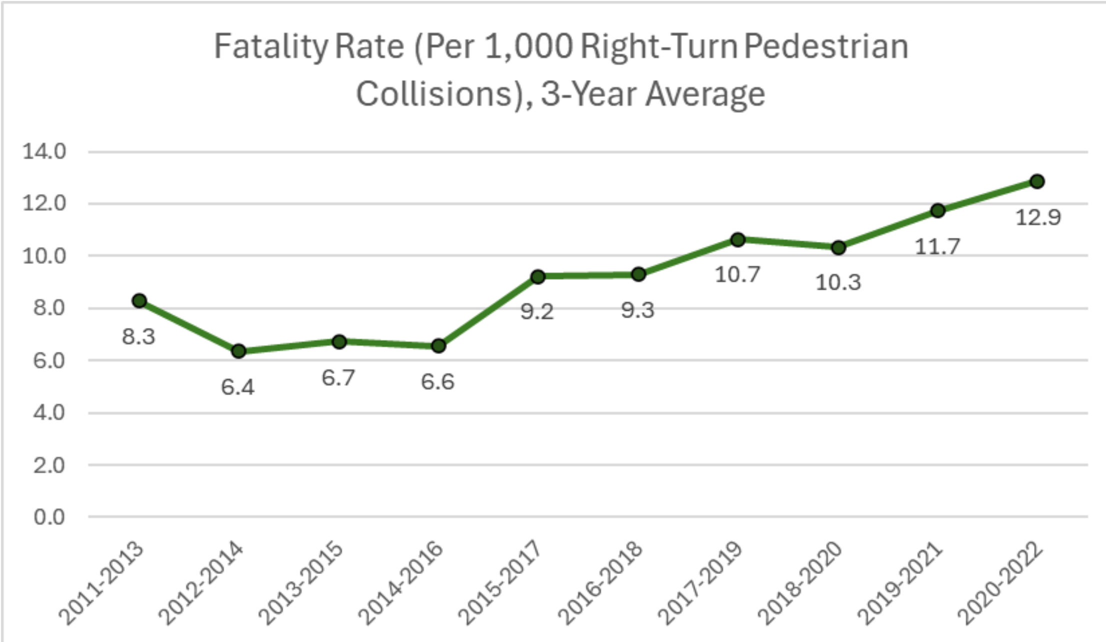
Table 1. Total RTOR Collisions Statewide (2011–2022)

	Right-Turn at Intersections		Yield Violations	
	Collisions	Fatalities	Collisions	Fatalities
Pedestrian	10,220	98	477	4
Cyclist	11,428	36	646	6
Automobile/ trucks	17,480	83	2,092	5

We also found that the proportion of RTOR crashes among all pedestrian crashes at signalized intersections was consistent with the findings from the literature that documented that RTOR crashes account for about 5 to 15 percent of pedestrian crashes at signalized intersections (Lord et al., 2002).

We then calculated the fatality rate for pedestrian collisions in which the driver attempted to make a right turn at an intersection preceding the collision. The fatality rate is defined as the number of fatalities per 1,000 collisions. As shown in Figure 4, the 3-year moving average for this fatality rate has been trending upwards in California.

Figure 4. 3-Year Moving Averages of the Fatality Rate (Per 1,000 Collisions) for Pedestrian Right-Turn Collisions at Signalized Intersections in CA



3.3 RTOR and Equity Issues

Methods

We conducted a statewide analysis of RTOR collisions to determine the impacts of socioeconomic variables on these collisions. We employed a statistical approach known as a generalized linear mixed model (GLMM) to fulfill our research objectives. This model enabled us to incorporate individual factors, such as race/ethnicity and collision circumstances, as well as neighborhood characteristics, such as SES scores, into our analysis. Additionally, we accounted for the hierarchical nature of our data, which was collected at the neighborhood level, ensuring that variations within neighborhoods were properly accounted for. We split our analysis into three groups—pedestrians, cyclists, and vehicles—to account for differences in how these groups experience collisions. Then, we further split pedestrian, cyclist, and vehicle collisions into two categories: right-turn violations and failure-to-yield violations.

The likelihood of a right-turn or failure-to-yield collision occurring was our dependent variable. Our focal predictor was socioeconomic status (SES) by census tract, which is calculated through a principal components analysis score (PCA) that includes median rent, home value, education level, and income. Other covariates included neighborhood characteristics (including racial composition and built environment), road characteristics (including speed limit and road type), collision characteristics (including speed, DUI status, weather, and time of day), and cyclist and pedestrian characteristics (including age and gender). A full list of variables for the model can be found in Tables 2 and 3.

Results

The dataset provides descriptive values primarily in the form of proportions, reported in Table 2, which can be interpreted as percentages. Approximately 11.1 percent of cyclist collisions are preceded by right turns, compared to 7.1 percent of pedestrian collisions. Instances of a failure to yield precede roughly 0.6 percent of cyclist collisions and 0.3 percent of pedestrian collisions. Regarding demographic breakdowns, most cyclists involved in collisions are white, accounting for 45.4 percent. In contrast, Hispanic individuals comprise the largest group of pedestrians involved in collisions, comprising 48.8 percent of cases.

When examining drivers involved in collisions, white individuals constitute the highest proportion among those who hit cyclists, at 34.3 percent. Similarly, the largest demographic group of drivers involved in collisions with pedestrians is also white, at 29.2 percent. Reckless behavior among drivers before collisions is relatively uncommon, with only 1.1 percent of drivers who hit cyclists found to be under the influence. Moreover, most collisions occurred in favorable weather conditions; for example, 96.9 percent of cyclist collisions occurred in dry weather. A notable portion of collisions occurred on major arterials, though not the majority; for instance, 18 percent of cyclist collisions and an unspecified percentage of pedestrian collisions occurred on major arterials. Most collisions occurred in suburban areas, comprising 41.1 percent of cyclist collisions and 37.2 percent of pedestrian collisions.

Table 2. Descriptive Values of Collisions

	Cyclist		Pedestrian	
Statistic	Mean	St. Dev.	Mean	St. Dev.
Right Turn	0.111	0.314	0.071	0.257
Yield	0.006	0.079	0.003	0.058
White (Ref)	0.454	0.498	0.306	0.461
Black	0.093	0.29	0.138	0.345
Hispanic	0.347	0.476	0.391	0.488
Asian	0.059	0.235	0.061	0.239
Other	0.047	0.213	0.051	0.22
Male	0.804	0.397	0.585	0.493
Age	35.834	18.062	38.862	21.073
Driver White (Ref)	0.343	0.475	0.292	0.455
Driver Black	0.078	0.269	0.094	0.292
Driver Hispanic	0.286	0.452	0.29	0.454
Driver Asian	0.081	0.273	0.073	0.261
Driver Other	0.062	0.241	0.057	0.232
Vehicle Driver Under Influence	0.011	0.102	0.021	0.144
Vehicle Driver Unsafe Speeds	0.04	0.196	0.061	0.239
Conditions Dark	0.02	0.14	0.068	0.251
Conditions Dry	0.969	0.173	0.932	0.251
Bad Weather	0.019	0.136	0.051	0.219
Major Arterial Road	0.18	0.384	0.187	0.39
Posted Speed Limit	27.67	7.223	27.608	7.829
Bicycle Infrastructure	0.18	0.384		
Bicycle Density	212.652	211.605		
Neighborhood Percent White (Ref)	39.313	25.846	32.08	24.652
Neighborhood Percent Black	5.675	8.076	7.343	10.112
Neighborhood Percent Asian	14.024	15.179	14.02	15.841

	Cyclist		Pedestrian	
Statistic	Mean	St. Dev.	Mean	St. Dev.
Neighborhood Percent Hispanic	36.958	26.689	42.767	27.185
Neighborhood SES	1.4	2.319	0.79	2.008
Urban Centers (Ref)	0.028	0.166	0.036	0.185
Compact Suburban Places	0.177	0.382	0.167	0.373
Suburban Places	0.41	0.492	0.372	0.483
Rural Places	0.035	0.185	0.026	0.16
Employment Centers	0.009	0.097	0.009	0.093
Special Districts	0.019	0.135	0.013	0.115
Walkability Score	13.572	3.178	13.865	2.97
	105,071		150,811	

GLMM Results

Understanding the odds ratios in Generalized Linear Mixed Models (GLMM), reported in Table 4, provides valuable insights into how various factors influence the likelihood of collisions being preceded by failures to yield or right turns at intersections, with notable distinctions based on whether the person involved was cycling or walking. For instance, the impact of race differs significantly between cyclists and pedestrians. Being Black increases the odds of a pedestrian being hit by a car by 2.3 percent (1-1.023*100), but this association does not extend to cyclists. Interestingly, Black cyclists face a higher likelihood of being hit by cars making right turns, whereas no such association is observed among Black pedestrians in these types of collisions. Another intriguing factor is neighborhood socioeconomic status (SES). Higher SES neighborhoods decrease the odds of pedestrians being hit by cars that fail to yield by 12.4 percent. However, paradoxically, higher SES increases the odds of pedestrians being hit by cars making right turns by 4.1 percent. SES decreases the chance that bicyclists will be hit by cars that make right turns; it has no relationship with cyclists hit by cars that fail to yield. This complexity underscores the nuanced relationship between socioeconomic factors and intersectional collision dynamics.

Factors traditionally linked to collisions, such as driving under the influence or exceeding speed limits, generally decrease the odds of collisions being preceded by right turns or failures to yield. For instance, being under the influence reduces the odds of a pedestrian being hit after a failure to yield by a substantial 89.6 percent. This suggests that such collisions may occur in different contexts or locations compared to other types. Conversely, a higher walkability score tends to increase the odds of collisions. Each point increase in walkability score raises the likelihood of pedestrians being hit by cars that failed to yield by 17.6 percent. This relationship underscores the complex interplay between urban design features and collision risks.

Certain predictors consistently influence collision likelihood across all types measured. For example, being on a major arterial road consistently raises the odds of collisions involving cyclists or pedestrians regardless of the type of collision considered. Similarly, higher posted speed limits correlate with increased collision odds in various contexts. Regarding location characteristics, suburban areas consistently show higher odds of collisions across all measured types. This suggests that urban form and density play significant roles in shaping collision risks, potentially due to differences in infrastructure, traffic patterns, and pedestrian behavior.

Table 3. GLMM Collisions, Odds Ratios

	Yield		Right	
Variables	Bicycle	Pedestrian	Bicycle	Pedestrian
Black	0.962	1.023***	1.043***	1.018
	(0.061)	(0.002)	(0.011)	(0.012)
Hispanic	0.993	1.078***	1.086***	1.042**
	(0.065)	(0.002)	(0.013)	(0.013)
Asian	1.027	0.905***	1.050***	1.007
	(0.049)	(0.002)	(0.011)	(0.011)
Other	1.010	0.968***	1.021	1.004
	(0.053)	(0.002)	(0.011)	(0.011)
Male	0.958	0.819***	0.928***	0.870***
	(0.052)	(0.002)	(0.010)	(0.010)
Age	1.139*	1.000	0.947***	1.001
	(0.052)	(0.002)	(0.011)	(0.010)
Driver Black	0.957	0.856***	1.048***	0.950***
	(0.068)	(0.002)	(0.011)	(0.011)
Driver Hispanic	1.128*	0.917***	1.105***	0.881***
	(0.061)	(0.002)	(0.012)	(0.012)
Driver Asian	1.132*	0.955***	1.091***	0.970**
	(0.048)	(0.002)	(0.010)	(0.010)
Driver Other	1.123*	0.973***	1.078***	0.966***
	(0.049)	(0.002)	(0.010)	(0.010)
Vehicle Driver Under Influence	0.294	0.104***	0.894***	0.831***

	Yield		Right	
Variables	Bicycle	Pedestrian	Bicycle	Pedestrian
	(18.367)	(0.002)	(0.016)	(0.018)
Vehicle Driver Unsafe Speeds	0.059	0.061***	0.903***	0.740***
	(65.304)	(0.002)	(0.012)	(0.018)
Conditions Dark	0.850	0.588***	0.835***	0.606***
	(0.095)	(0.002)	(0.018)	(0.026)
Conditions Dry	0.955	1.075***	1.007	1.015
	(0.069)	(0.002)	(0.015)	(0.018)
Bad Weather	1.017	0.996*	1.008	0.985
	(0.068)	(0.002)	(0.014)	(0.018)
Major Arterial Road	1.217***	1.141***	1.069***	1.104***
	(0.057)	(0.002)	(0.011)	(0.012)
Posted Speed Limit	1.182***	1.228***	1.050***	1.063***
	(0.044)	(0.002)	(0.012)	(0.013)
Bicycle Infrastructure	0.851*		0.993	
	(0.064)		(0.011)	
Bicycle Density	0.801		0.900***	
	(0.117)		(0.017)	
Neighborhood Percent Black	1.086	0.835***	0.993	0.974
	(0.084)	(0.002)	(0.014)	(0.016)
Neighborhood Percent Asian	1.182*	1.083***	1.055***	1.082***
	(0.079)	(0.002)	(0.014)	(0.015)
Neighborhood Percent Hispanic	1.018	0.781***	0.992	0.993

	Yield		Right	
Variables	Bicycle	Pedestrian	Bicycle	Pedestrian
	(0.120)	(0.002)	(0.020)	(0.021)
Neighborhood SES	1.002	0.876***	0.888***	1.041*
	(0.120)	(0.002)	(0.020)	(0.019)
Compact Suburban Places	1.167	1.095***	1.078***	1.033*
	(0.093)	(0.002)	(0.015)	(0.014)
Suburban Places	1.389**	1.206***	1.129***	1.090***
	(0.111)	(0.002)	(0.017)	(0.017)
Rural Places	0.845	0.949***	0.852***	0.906***
	(0.162)	(0.002)	(0.021)	(0.021)
Employment Centers	1.082	1.125***	1.032*	1.015
	(0.077)	(0.002)	(0.015)	(0.015)
Special Districts	1.016	1.087***	0.991	1.013
	(0.089)	(0.002)	(0.015)	(0.013)
Walkability Score	1.129	1.176***	1.128***	1.077***
	(0.105)	(0.002)	(0.017)	(0.017)
Constant	0.001	0.00004***	0.105***	0.059***
	(13.446)	(0.002)	(0.014)	(0.016)
Observations	105,071	150,811	105,071	150,811
Log Likelihood	-3,706.657	-3,096.481	-35,512.600	-37,286.030

*p<0.050; **p<0.010; ***p<0.001; Predictors Scaled

To better understand the SES results, we plot their predicted values in Figures 5–7. These figures effectively show how the chance of collisions changes with each higher degree of SES, with all the other relevant variables being controlled for. As they show, reflecting our models, SES increases the chance of pedestrians being hit at right turns while it decreases the chance for cyclists. SES decreases the chance of pedestrians being hit by cars that fail to yield, but it has no relationship with cyclists.

Figure 5. Predicted Probability by Scaled Socioeconomic Status for Collisions Involving a Pedestrian in which the Driver Made a Right Turn at an Intersection before the Collision

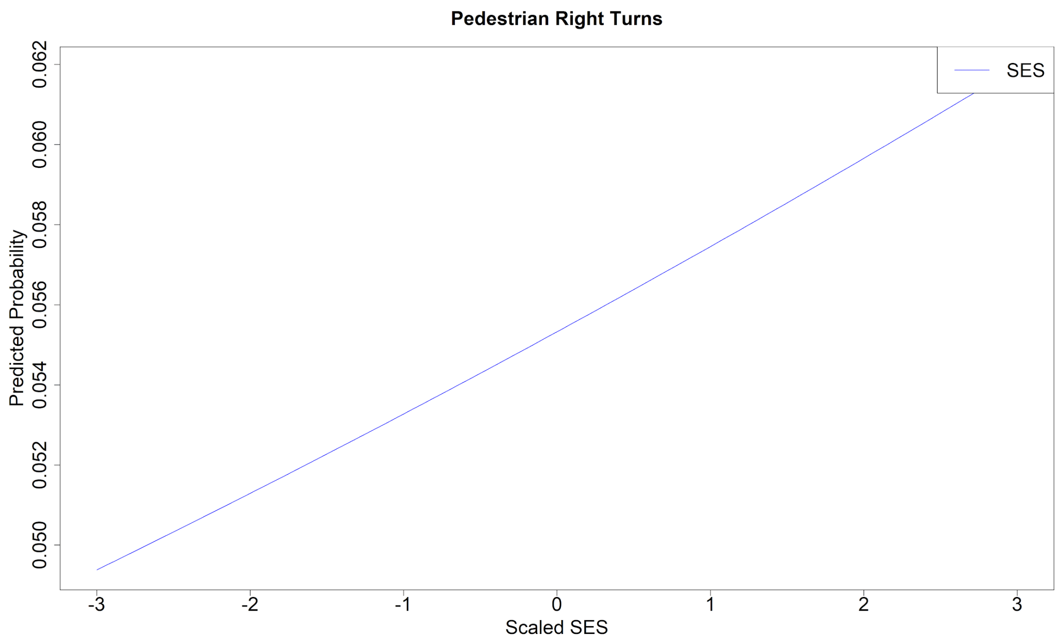


Figure 6. Predicted Probability by Scaled Socioeconomic Status for Collisions Involving a Bicyclist in which the Driver Made a Right Turn at an Intersection Before the Collision

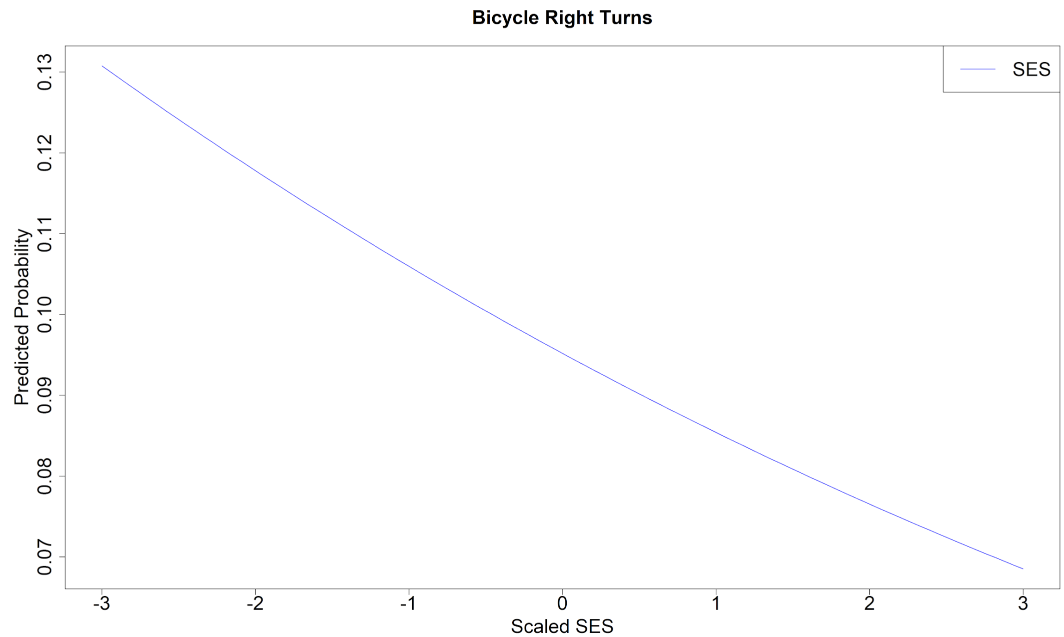
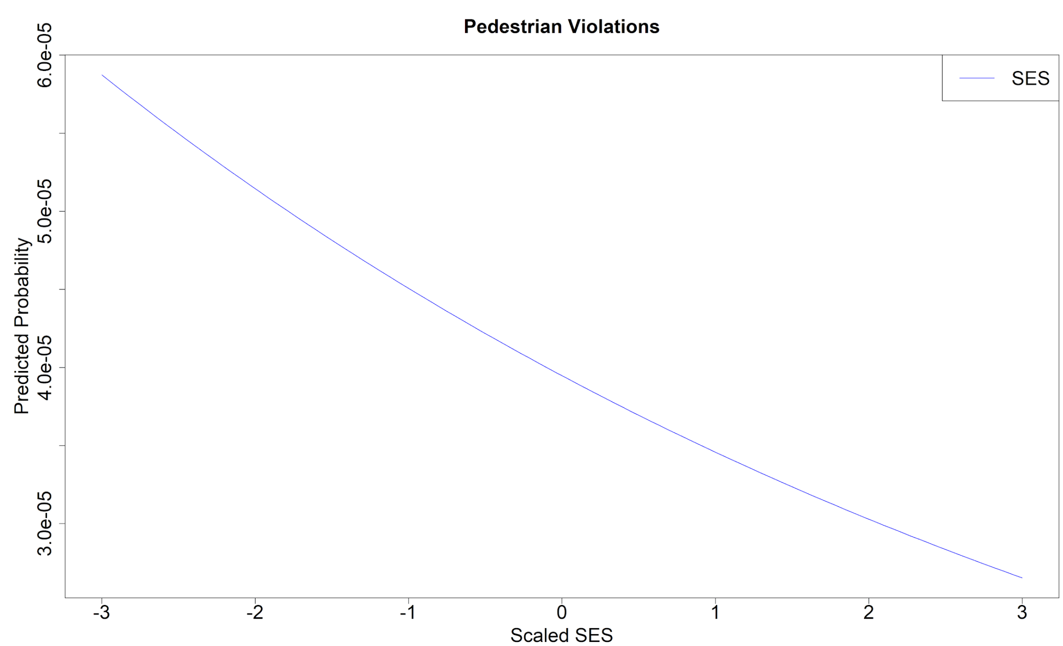


Figure 7. Predicted Probability by Scaled Socioeconomic Status for Collisions Involving a Pedestrian in which the Driver Did Not Yield



3.4 Intersection Case Studies

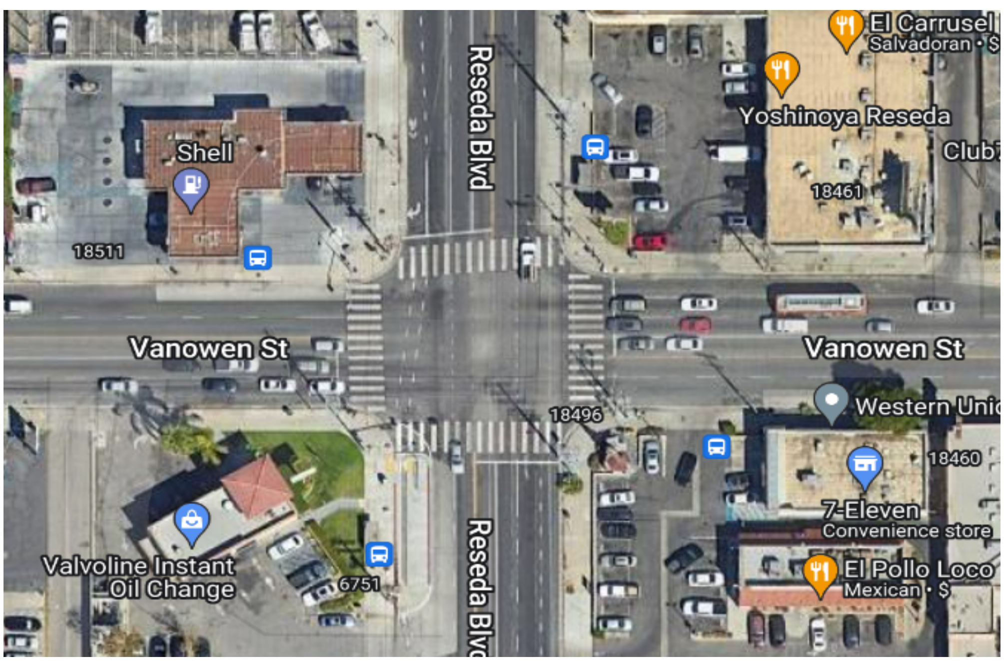
Methodology

To identify intersection characteristics that could be increasing the likelihood of RTOR collisions, we conducted a case study of the City of Los Angeles. We chose this study area because the city has a dataset of all intersections publicly available. As with previous analyses, we split our dataset into three parts: pedestrian, cyclist, and vehicle collisions. Due to the relatively small number of yield-violation collisions, we only looked at collisions involving a right turn at an intersection. With each group we used a spatial join to identify these types of collisions within a 50-foot buffer of each intersection. Then, we viewed common characteristics at the intersections with the highest numbers of right-turn collisions.

Common Characteristics

We found several common characteristics of intersections with the highest numbers of right-turn collisions. The most prevalent was that very few of these intersections contained a protected cycle lane. Additionally, most of these intersections were located near transit stops, likely resulting in a higher volume of pedestrians. We also found that these intersections were located in commercial areas with large parking lots and relatively heavy, fast-moving cross traffic. Additionally, several intersections had irregular designs that could add to confusion or distraction amongst drivers. Figure 8 displays an example of one intersection with many pedestrian collisions involving right turns at an intersection (6 in 12 years), Vanowen Street at Reseda Boulevard.

Figure 8: Vanowen Street at Reseda Boulevard intersection, Los Angeles



Source: Google Maps

4. Discussion

Safe Systems Context

A key pillar of the Safe Systems approach promoted by the FHWA (Federal Highway Administration) states that, "[s]afety is proactive, and therefore, we should identify and mitigate latent risks in the transportation system, rather than waiting for crashes to occur and reacting afterward" (FHWA, n.d.). We make the case that considering limiting and prohibiting RTOR is imperative under the Safe Systems approach.

Overall, the data showed that right-turn collisions at signalized intersections were responsible for over 39,000 collisions and 217 fatalities (involving pedestrians, bicyclists, and drivers) between 2011–2022 in the state of California. Over half (21,648) of these collisions and 134 fatalities involved a pedestrian or cyclist. Our crash data analysis along with the literature leads us to the conclusion that RTOR movements are generally unsafe for pedestrians, bicyclists, and drivers, hindering the livability of streets for vulnerable road users. Additionally, RTOR movements are only marginally useful in lowering emissions and only in certain contexts. Those marginal benefits have declined over the years as ICEV technology has improved and will likely further decline with increased EV adoption.

Given the number of conflicts associated with RTOR movements, they lower comfort levels for active travelers and livability, which have serious implications in terms of physical activity, mental health, street livability, and encouraging walking and bicycling. In a July 2023 memo expanding the use of restrictions on RTOR, SFMTA noted that "... even if close calls or blocked crosswalks due to vehicular turns on red did not always lead to injury crashes, they degraded the walking environment and the priority that pedestrians should have when crossing a street" (Olea, 2023).

Communities and agency professionals use the number of VRUs using an intersection as a stand-in measure for such conflicts. Relevant MUTCD guidelines on the prohibition of RTOR at individual intersections in Section 2B-54 include an "unacceptable number of pedestrian conflicts with right-turn-on-red maneuvers, especially involving children, older pedestrians, or persons with disabilities" as one of the conditions that may be used to consider the RTOR prohibition (FHWA, 2009). For communities that want to increase active travel rates, it makes sense to create a more welcoming environment for active modes of travel through intersections by prohibiting RTOR proactively even though the crash statistics have not yet become alarming.

Two other national statistics that are seemingly unrelated but when put together point to the need for limiting RTOR at intersections are as follows:

- A recent Insurance Institute for Highway Safety (IIHS) study pointed out that the odds of a pedestrian fatality in case of a crash that involved a right turn by an automobile were 89 percent higher for pickups and 63 percent higher for SUVs than for passenger cars (IIHS, 2022).

- Close to 4 out of 5 new personal automobiles (78.5 percent) sold in the US in 2021 were pickup trucks or SUVs, and that number used to be close to half (52.1 percent) as recently as 2013 (Shilling, 2022; Goughnour et al., 2018).

Putting these statistics together, it is clear that the automobile fleet in the US is changing in a way that makes RTOR collisions deadlier. This change is likely a major contributor to the increasing trend in the 3-year moving average of the fatality rate of right-turn pedestrian-automobile collisions at signalized intersections (shown in Figure 4 based on California crash data). This trend does not even reflect the adoption of heavier and faster accelerating EVs. Hence, the existing crash data and fatality rates likely underestimate the future risk to pedestrians from RTOR maneuvers at signalized intersections. Therefore, a Safe Systems approach demands that states adopt policies that address this challenge immediately, rather than waiting for the pedestrian fatalities involving RTOR maneuvers to rise even faster.

5. Policy Options and Recommendations

The introduction of permissive right-turn-on-red (RTOR) in the 1970s has had negative consequences for pedestrian and bicyclist safety. Drivers often focus on traffic from the left, overlooking pedestrians on the right, or they may block intersections while waiting to turn. Our research shows that the prohibition of RTOR movements is consistent with the Safe Systems approach. Communities that want to create a VRU-friendly environment and promote active travel can benefit from RTOR prohibition. The question is how to accomplish this as safely, clearly, and cost-effectively as possible.

One of the most fundamental changes to improve safety during RTOR maneuvers is ensuring drivers stop at the red light before proceeding, meaning that the current law is followed and enforced appropriately. Greater police enforcement coupled with public messaging campaigns may help ensure that all drivers at least come to a full stop before making the right turn at a red light. However, doing so in an equitable manner may require automated enforcement, potentially via the use of red-light cameras, which may be a harder political issue to address and is beyond the scope of this work. The following sections discuss potential changes to the existing laws governing RTOR, recommending that states consider helping individual communities to make context-sensitive decisions about RTOR.

Statewide Prohibition

Instituting a statewide ban on RTOR movements would most likely be the safest, clearest, and least confusing policy action to take. However, our analysis suggests that decisions to ban or permit RTOR movements should take into consideration the specific contexts of each city. A blanket statewide policy prescription could create an undue burden on cities that want to permit or prohibit RTOR at a vast number of intersections in terms of signage.

Delegating Prohibition/Permitting Authority to Individual Communities

We recommend that cities be able to determine whether they want to ban or allow RTOR movements and then place signs at their borders and at intersections according to whether it is permitted or not, based on the specific contextual factors of the types of places and intersections they have and want to have.

Rather than trying to prohibit RTOR movements on an intersection-by-intersection basis and provide required signage, which could be expensive and logistically challenging, the law should allow cities to institute a blanket prohibition (or permission) of RTOR movements. This remains our preferred policy option. In this case, the state would allow cities to elect to ban RTOR as the default at intersections and then indicate intersections where the maneuver will be permitted. Cities could decide where to allow RTOR based on their prevailing place typology, intersection design, presence of pedestrians and cyclists, and proximity to transit stations.

An important implementation factor to consider is that prohibiting RTOR can increase conflicts during the right-turn-on-green (RTOG) maneuver with concurrent signals (Goughnour et al., 2018). Therefore, the RTOR prohibition should prompt the implementation of leading pedestrian intervals (LPIs). LPIs give pedestrians a head start of three to seven seconds before parallel traffic is allowed to turn right, improving pedestrian safety. Cities adopting blanket prohibition under this state law change should be required to have LPIs implemented at all signalized intersections. LPIs could be used alongside flashing yellow arrows (FYAs) for right turns. A study by Jashami et al. (2019) conducted in Oregon examined driver comprehension and behavior regarding right turn FYAs, considering factors such as signal indication type, active display, length of the right-turn bay, and pedestrian presence. The study found that right turn FYAs improve driver comprehension and caution when turning, leading to better yielding behavior towards pedestrians.

Another set of options for cities may be a partial prohibition. Cities could ban RTOR at new intersections or intersections that are being redesigned, an approach that Seattle has recently implemented. Additionally, cities could ban RTOR at intersections with transit stops or within transit priority areas, which are known for having a greater density of pedestrians and cyclists. A major downside to this approach is cost, as cities would have to add signage at every intersection that they want to ban RTOR. Furthermore, as noted in the literature (Retting et al., 2002) partial prohibitions are not as effective in reducing conflicts.

With any of these approaches, including the preferred statewide policy option, community engagement and outreach will be vital steps in the implementation process. In sum, taking into consideration all the street safety and livability considerations, weighed against the limited (and expected to go lower) emission-reduction and energy-saving effects, states should rewrite their laws to make it easier for communities to make context-sensitive RTOR practices. Our recommendations are based on the fact that prohibiting RTOR is a key part of implementing the Safe Systems approach, especially for communities that want to promote active travel.

Appendix A

There are five conflicting movements for automobiles making a right-turn-on-red maneuver on a 4-legged signalized intersection. Two of these movements are pedestrian crossing movements, and one is from bicycle traffic running parallel to traffic movement. There are also two conflicting automobile movements; one is left-turning traffic from the opposing direction and the other is through movement from the perpendicular direction. The probability of stopping multiple times is dependent on the volume of these conflicting movements and the queue length of the traffic stored in front of the vehicle turning right.

The total emissions for right-turning traffic thus can be expressed as equation 1.

$$E_v = p(0).\rho_v(u).\frac{L}{u} + p(1).\rho_v'(u).t_{acc} + 2.p(2).\rho_v'(u).t_{acc} + \cdots \ldots \ldots .. \qquad \text{(equation 1)}$$

Where:

- p(0) = probability of stopping 0 times
- p(1) = probability of stopping once
- p(2) = probability of stopping twice
- $p_v(u)$ = emissions rate at cruising speed, u (grams/second) for vehicle, v
- $p'_v(u)$ = emissions rate for accelerating to speed, u from stopped/idle condition (grams/second)
- t_{acc} = number of seconds accelerating
- L = length of the right turn influence area
- E_v = total emissions for vehicle, v in a right turn

Equation 1 assumes that the idle emissions are negligible compared to the emissions during the acceleration maneuver. This assumption is based on most modern ICEV vehicles having an engine turn-off function in idle states. Even if the engines are not turned off, vehicle designs account for the idle condition and run on a low engine demand state that produces minimal emissions. Also, for a small intersection influence area (L), the contribution of acceleration in emissions is far greater than the cruising part.

Acronyms and Abbreviations

CMF	Crash Modification Factor
EV	Electric Vehicle
FYA	Flashing Yellow Arrow
FHWA	Federal Highway Administration
GLMM	Generalized Linear Mixed Models
ICEV	Internal Combustion Engine Vehicles
IIHS	Insurance Institute for Highway Safety
LPI	Leading Pedestrian Intervals
MUTCD	Manual on Uniform Traffic Control Devices
NACTO	National Association of City Transportation Officials
NHTSA	National Highway Traffic Safety Administration
NCDOT	North Carolina Department of Transportation
NTOR	No Turn on Red
PCA	Principal Components Analysis
RTOG	Right Turn on Green
RTOR	Right Turn on Red
SES	Socioeconomic Status
SLD	Smart Location Database
SWITRS	Statewide Integrated Traffic Records System
VRU	Vulnerable Road User

Bibliography

American Association of State Transportation Officials. (2010). Highway safety manual (1st ed., Vol. 1). American Association of State Highway and Transportation Officials.

Appleyard, Bruce, & Appleyard, Donald. (2020). *Livable streets 2.0.* Elsevier. https://doi.org/10.1016/C2016-0-05005-2

Appleyard, Donald. (1981). *Livable streets.* University of California Press.

California Energy Commission. (2024, May 1). *Zero-emission vehicle sales remain strong in California*. California Energy Commission. https://www.energy.ca.gov/news/2024-05/zero-emission-vehicle-sales-remain-strong-california

California Vehicle Code, 21453, Section B.

California Office of Traffic Safety. *What is a safe system approach?* https://www.ots.ca.gov/the-safe-system/

Caltrans. CA MUTCD. Retrieved July 3, 2024, from https://dot.ca.gov/programs/safety-programs/camutcd

City of Los Angeles. Los Angeles Geohub.

CMF Clearinghouse. (n.d.). Retrieved July 3, 2024, from https://www.cmfclearinghouse.org/userguide_clearinghouse.php

Coelho, M. C., Farias, T. L., & Rouphail, N. M. (2005). Impact of speed control traffic signals on pollutant emissions. *Transportation Research. Part D, Transport and Environment*, *10*(4), 323–340. https://doi.org/10.1016/j.trd.2005.04.005

Compton, Richard, & Milton, Edward. (1994). *Safety impact of permitting right-turn-on-red: A report to Congress by the National Highway Traffic Safety Administration.* National Highway Traffic Safety Administration.

Connecticut Department of Transportation. (2024). *No turn on red report.* https://portal.ct.gov/-/media/dot/documents/dvisionzero/ntor-report.pdf

Cunningham, Chris, Pyo, Kihyun, Baek, Juwoon, Byrom, Elizabeth, & Warchol, Shannon. (2020). Guidelines for Implementation of Right Turn Flashing Yellow Arrows and Leading Pedestrian Intervals (No. FHWA/NC/2018-21). North Carolina. Dept. of Transportation.

Darma, Y., Karim, M. R., Mohamad, J., & Abdullah, S. (2005, January). Control delay variability at signalized intersection based on HCM method. *Proceedings of the Eastern Asia Society for Transportation Studies,* 5, 945–958.

D.C. Law 24-214. Safer Streets Amendment Act of 2022. | D.C. Law Library. https://code.dccouncil.gov/us/dc/council/laws/24-214. Accessed Aug. 1, 2024.

Goughnour, E., Carter, D., Lyon, C., Persaud, B., Lan, B., Chun, P., Signor, K. (2018). Safety Evaluation of Protected Left Turn Phasing and Leading Pedestrian Intervals on Pedestrian Safety, Federal Highway Administration, Report No. FHWA-HRT-18-044. Washington, D.C.

Guo, Y., Liu, P., Wu, Y., & Chen, J. (2018). Evaluating how right-turn treatments affect right-turn-on-red conflicts at signalized intersections. Journal of Transportation Safety & Security, 12(3), 419–440. https://doi.org/10.1080/19439962.2018.1490368

Federal Highway Administration. Manual on Uniform Traffic Control Devices for Streets and Highways. (2009). Federal Highway Administration, U.S. Department of Transportation, Washington, D.C.

Federal Highway Administration. Safety Evaluation of Leading Pedestrian Intervals on Pedestrian Safety. (2018). Publication No. FHWA-HRT-18-060, U.S. Department of Transportation, Washington, D.C.

Federal Highway Administration. (n.d.). The Safe System Approach Flyer. https://safety.fhwa.dot.gov/zerodeaths/docs/FHWA_SafeSystem_Brochure_V9_508_200717.pdf

Fleck, Jack, & Yee, Bond. (2002). Safety evaluation of right turn on red. *ITE Journal.*

Frost, Alexander, Appleyard, Bruce, Gibbons, Joseph, & Ryan, Sherry. (2018). Quantifying the sustainability, livability, and equity performance of urban and suburban places in California. *Transportation Research Record, 2672*(3). doi:10.1177/0361198118791382

Hurwitz, D., Monsere, C., Kothuri, S., Jashami, H., Buker, K., & Kading, A. (2018). Improved safety and efficiency of protected/permitted right-turns in Oregon (No. FHWA-OR-RD-18-14). Oregon. Dept. of Transportation. Research Section.

Insurance Institute for Highway Safety. (2022). SUVs, other large vehicles often hit pedestrians while turning. https://www.iihs.org/news/detail/suvs-other-large-vehicles-often-hit-pedestrians-while-turning

Islam, Ahadul, Mekker, Michelle, & Singleton, Patrick. (2022). Examining pedestrian crash frequency, severity, and safety in numbers using pedestrian exposure from Utah traffic signal data. *Journal of Transportation Engineering, Part A: Systems, 148*(10). https://doi.org/10.1061/JTEPBS.0000737

Lin C, Zhou X, Wu D, Gong B. Estimation of Emissions at Signalized Intersections Using an Improved MOVES Model with GPS Data. (2019). *Int J Environ Res Public Health*,16(19):3647. doi: 10.3390/ijerph16193647

Jashami, H., Hurwitz, D.S., Monsere, C., Kothuri, S. (2019). Evaluation of Driver Comprehension and Visual Attention of the Flashing Yellow Arrow Display for Permissive Right Turns. Transportation Research Record, Vol.2673(1). pp.397–407.

Lieberman, Edward, & Cohen, Stephen. (1976). New technique for evaluating urban traffic energy consumption and emissions. *Transportation Research Record, 599*, 41–45.

Listgarten, Sherry. (2024). Vehicles turning right pose a danger to cyclists and pedestrians. *The Almanac*.

Lord, Dominique. (2002, November). Synthesis on the safety of right turn on red in the United States and Canada. In 82nd Annual Meeting of the Transportation Research Board. Washington, D.C.

Minnesota Department of Transportation. (n.d.). Traffic engineering: Flashing yellow arrow traffic signals. Flashing Yellow Arrow Traffic Signals - Traffic Engineering - MnDOT. https://www.dot.state.mn.us/trafficeng/signals/flashingyellowarrow.html

National Association of City Transportation Officials. (2020, October 15). *Protected Intersections*. https://nacto.org/publication/protected-intersections

Olea, R. (2023). MEMORANDUM: No turn on red regulations. https://lede-admin.sf.streetsblog.org/wp-content/uploads/sites/47/2024/04/No-turn-on-red-policy-July-2023.pdf

Packer, R. (2023). No right turn on red is now the default in Seattle. *The Urbanist.* https://www.theurbanist.org/2023/05/04/no-right-turn-on-red-is-now-the-default-in-seattle/

Pandian, S., Gokhale, S., & Ghoshal, A. K. (2009). Evaluating effects of traffic and vehicle characteristics on vehicular emissions near traffic intersections. Transportation Research Part D: Transport and Environment, 14(3), 180–196.

Reish, L. Comparing Demographic Trends in Vulnerable Road User Fatalities and the US Population, 1980–2019 (Research Note. Report No. DOT HS 813 178). *National Highway Traffic Safety Administration*, 2021.

Retting, R. A., Nitzburg, M. S., Farmer, C. M., & Knoblauch, R. L. (2002). Field evaluation of two methods for restricting right turn on red to promote pedestrian safety. ITE journal, 72(1), 32–36.

Right Turn on Red in Staten Island NYC311. https://portal.311.nyc.gov/article/?kanumber=KA-01354. Accessed Aug. 1, 2024.

Rouphail, N.M., Frey, H.C., Colyar, J.D., Unal, A. (2001). Vehicle emissions and traffic measures: exploratory analysis of field observations at signalised arterials. In: Proceedings of the 80th Annual Meeting of the Transportation Research Board, Washington, D.C.

Seattle Department of Transportation. (2023). *Vision Zero: Top-to-Bottom Review.* https://www.seattle.gov/transportation/projects-and-programs/safety-first/vision-zero/vision-zero-review

Shilling, E. (2022). Trucks And SUVs Are Now Over 80 Percent of New Car Sales in The U.S. *Jalopnik.* https://jalopnik.com/trucks-and-suvs-are-now-over-80-percent-of-new-car-sale-1848427797

Statewide Integrated Traffic Records System. (2024).

Steinman, N., & Hines, D. (2004). Methodology to Assess Design Features for Pedestrian and Bicyclist Crossings at Signalized Intersections. Transportation Research Record: Journal of the Transportation Research Board, 1878, 42–50. doi:10.3141/1878-06

Taplin, T. Budget referral: No right on red signs. Nov, 2022.

UC Davis Bicycling Plus Research Collaborative. (2022). *California active transportation benefit-cost tool.* https://activetravelbenefits.ucdavis.edu/

US Census Bureau. *American community survey 2015–2019*. https://www.census.gov/programs-surveys/acs/about.html

US Environmental Protection Agency. *Smart Location Database*. https://www.epa.gov/smartgrowth/smart-location-mapping#walkability

US Environmental Protection Agency. (2021). *National walkability index: Methodology and user guide.* https://www.epa.gov/sites/default/files/2021-06/documents/national_walkability_index_methodology_and_user_guide_june2021.pdf

Wolfgram, Joshua, Fish, Robin, Raja, Wasim, & Jain, Rahul. (2022). Analysis of expanded no turn on red applications in Washington, DC, USA. Institute of Transportation Engineers. *ITE Journal, 92*(5), 40–44.

Wu, J., & Xu, H. (2017). Driver behavior analysis for right-turn drivers at signalized intersections using SHRP 2 naturalistic driving study data. *Journal of Safety Research*, *63*, 177–185. https://doi.org/10.1016/j.jsr.2017.10.010

Yan, X., Abdel-Aty, M., Radwan, E., Wang, X., & Chilakapati, P. (2008). Validating a driving simulator using surrogate safety measures. *Accident Analysis & Prevention*, *40*(1), 274–288. https://doi.org/10.1016/j.aap.2007.06.007

Yi, Q., Chen, X., & Li, D. (2012). *Evaluating safety performance and developing guidelines for the use of right turn on red* (RTOR). Center for Transportation Training and Research.

Zador, P., Moshman, J., & Marcus, L. (1982). Adoption of right turn on red: Effects on crashes at signalized intersections. *Accident Analysis & Prevention*, *14*(3), 219–234. https://doi.org/10.1016/0001-4575(82)90033-1

Zador, P. L. (1984). Right-turn-on-red laws and motor vehicle crashes: A review of the literature. *Accident Analysis & Prevention*, *16*(4), 241–245. https://doi.org/10.1016/0001-4575(84)90019-8

Zegeer, C.V., K.S. Opiela, and M.J. Cynecki. (1983). Pedestrian Signalization Alternatives. Report No.FHWA/RD-83-102. Washington, D.C.: FHWA.

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