CPBS Center for Pedestrian and Bicyclist Safety

A Tier-1 University Transportation Center

Safety Evaluation of Turning Maneuvers at California Intersections

July 2024	A Report From the Center for Pedestrian and Bicyclist Safety

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The Center for Pedestrian and Bicyclist Safety (CPBS) is a consortium of universities committed to eliminating pedestrian and bicyclist fatalities and injuries through cutting-edge research, workforce development, technology transfer, and education. Consortium members include: The University of New Mexico; San Diego State University; The University of California Berkeley; The University of Tennessee Knoxville; and The University of Wisconsin Milwaukee. More information can be found at: https://pedbikesafety.org

Disclaimer

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APPROXIMATE CONVERSIONS TO SI UNITS				
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		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa
APPROXIMATE CONVERSIONS FROM SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

Safety Evaluation of Turning Maneuvers at California Intersections

A Center for Pedestrian and Bicyclist Safety Research Report

July 2024

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Acronyms, Abbreviations, and Symbols

EV	Electric Vehicle
GLMM	Generalized Linear Mixed Models
MUTCD	Manual on Uniform Traffic Control Devices
RTOR	Right Turn on Red
SES	socioeconomic status
SWITRS	Statewide Integrated Traffic Records System

Abstract

We reviewed RTOR collisions throughout the state and found that right-turn collisions at intersections were responsible for over 39,000 collisions and 217 fatalities involving pedestrians, bicyclists, and drivers between 2011-2022. Over half of these collisions involved a pedestrian or cyclist. Our findings are that RTOR movements are generally unsafe for pedestrians, bicyclists, and drivers, seriously degrade street livability for vulnerable road users, while only marginally useful in lowering emissions, and under only certain contexts. We also find that RTOR collisions inequitably burden low socioeconomic status neighborhoods. Those marginal benefits may decline with increased electric vehicle (EV) adoption. We broadly recommend that state policy make it easier for California communities to prohibit RTOR movements. We recognize, however, that banning or permitting RTOR movements should consider the specific contexts of the communities (their place types), which could unduly burden cities that want to permit or prohibit RTOR at a vast number of their intersections in terms of signage.

Executive Summary

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 in order to receive federal assistance for mandated conservation programs. Since 1980, all states have permitted right turns on red generally, 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.

This research set out to understand the 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 also looked at the issues around emissions for RTOR maneuvers.

As part of our exploratory analysis, we created an Atlas of RTOR collisions throughout California, including a breakdown of RTOR collisions by different place types as well as identifying intersections where high numbers of RTOR collisions were occurring to conduct a series of case studies, so we could identify the common factors. During this exploratory analysis, 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.

Understanding odds ratios in Generalized Linear Mixed Models (GLMM), reveals 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 driver failures to yield to pedestrian collisions but paradoxically increases right-turn collision odds. High 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 located 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 amongst drivers.

Our findings are that RTOR movements are generally unsafe for pedestrians, bicyclists and drivers, while only marginally useful in lowering emissions, and under only certain contexts. Furthermore, they damage the livability of intersections for vulnerable road users, likely undermining travel by

walking or rolling. In sum, we recommend, in general, to prohibit RTOR movements. We recognize, however, that banning or permitting RTOR movements should take into account the specific contexts of the cities (their place types), which could unduly burden cities who 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, or not, citywide, and then sign intersections according to whether they are permitted or prohibited, based on their specific contextual factors of the types of places and intersections they have, and the type of city they want to be.

Introduction

There is a growing interest in right turn on red (RTOR) policies in order to improve pedestrian and bicycle safety, but there is a serious lack of research on the subject that can help states make policies that can guide communities in making informed decisions. One of the first books to critically assess right turn on red (RTOR) policies was the 1981 book Livable Streets, written by the PI's father, Donald Appleyard. This book has since been updated into Livable Streets 2.0, with new content on RTOR policies and practices.

Since 1939, California has permitted vehicles to make a right turn on a red light. When Congress passed the Energy Policy and Conservation Act of 1975, they included a provision requiring states to permit right turns on red lights to receive federal assistance for mandated conservation programs. Since 1980, all states have permitted right turns on red as a general rule. The National Highway Traffic Safety Administration submitted a report to Congress in 1994 to evaluate the policy on safety. 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 where a right turn on red is permitted. The report indicated that 44 percent of the crashes involved a pedestrian and 10 percent involved a bicyclist. In total, right turn-on red crashes represented .06 percent of the total number of fatal crashes in those four states, which seemed to say that RTOR crashes are not much of a problem, but the study "seems skewed".

Recently, Washington D.C. has banned making right turns on red, joining New York City, in an effort to protect pedestrians. The City of Berkeley is also considering a similar proposal. Given the recent interest in active modes of travel and recent data showing pedestrian and bicyclist fatalities rising at a faster rate than automobile occupants points to the urgency of this question. Adopting a safe systems approach that addresses conditions that lead to collisions and not just treating the hotspots would be key to addressing the issue.

More research on pedestrian and bicyclist injuries at intersections with a focus on the potential danger of right turns on red is needed to help jurisdictions make more informed decisions when considering this change to reduce traffic fatalities to zero.

Literature Review

The Debate Over RTOR

The passing of traffic laws allowing right turns on red lights (RTOR) in many states has led to a contentious debate amongst urban researchers, policymakers, and road users. Those in favor of leaving RTOR in place cite a low risk to traffic safety and increased efficiency. Those in favor of banning RTOR argue that it creates an unfriendly environment for cyclists and pedestrians, as well as an unacceptable increase in collisions.

Researchers and policymakers who advocate for RTOR policies to remain in place argue that RTOR results in minimal harm and improves traffic flow and fuel efficiency. For example, Dominique Lord (2002) analyzed crash statistics in the United States and Canada and concluded that the safety impacts of RTOR were minimal, citing the low speed of drivers who are performing a right turn on red and a low proportion of pedestrian crashes. Fleck and Yee (2002) also argued that collisions due to this maneuver are low, even in the dense, pedestrian-oriented environment of San Francisco.

However, other researchers have found that RTOR has resulted in an unacceptable increase in collisions, particularly amongst pedestrians, and should be banned at intersections with high pedestrian volume or high collision rates. Paul Zador's 1982 study found that there was a "highly significant increase in right turn crashes at signalized intersections after the adoption of RTOR" (p. 226). These increases were larger amongst pedestrians, particularly elderly pedestrians. His 1984 literature review of RTOR studies also draws the same conclusions, stating 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). Conversely, researchers have found that banning RTOR can create a safer road environment. In a study of Washington, D.C., 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; they had a decrease in expected pedestrian crashes by 37%. The City of Seattle reported decreases in vehicle-vulnerable road user conflicts as well after they made prohibiting RTOR at intersections the default setting at new or modified intersections. The city instituted the policy after a 'top-to-bottom' review of its Vision Zero program (Seattle Department of Transportation, 2023; Packer, 2023).

Previous studies have explored some of the 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 (Qi et al, 2012).

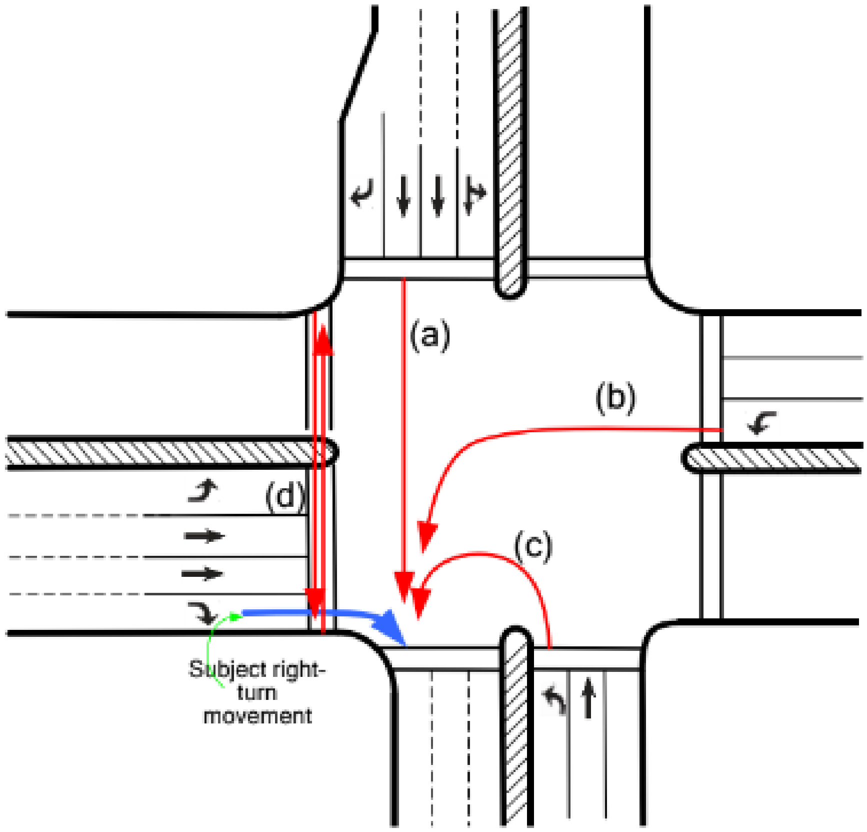

Figure 1. "Illustration of movements potentially conflicting with RTOR vehicles" Copied from Qi et al, 2012.

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. 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% of drivers did not stop at the limit line before starting their turn (Yan et al, 2007). 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 and Xu, 2017). This conflict is demonstrated in figure 2.

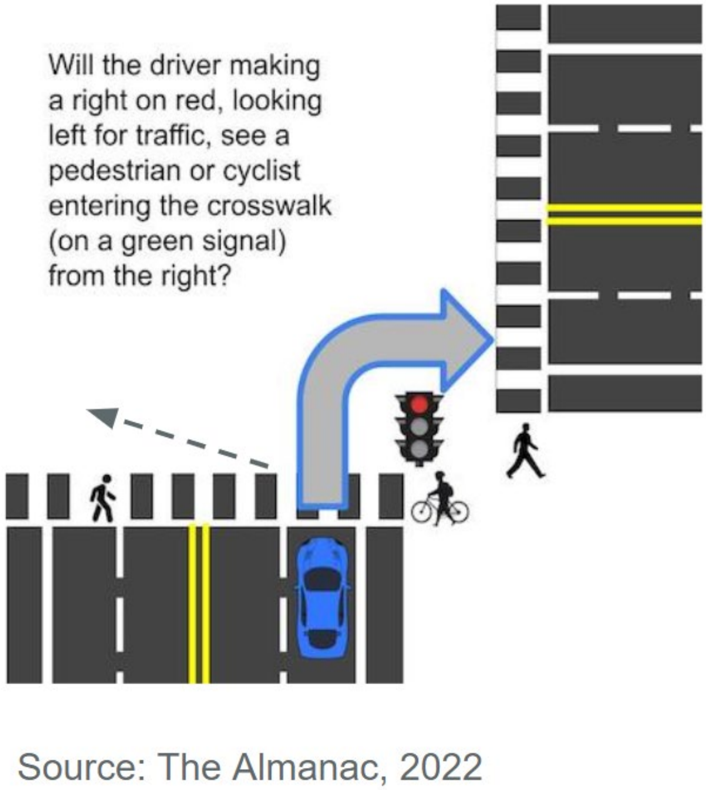

Figure 2. Potential vehicle-pedestrian conflict due to permitting RTOR. Copied from The Almanac, 2022.

Studies on RTOR - Associated Emissions Reductions

As more drivers continue to take right turns at red lights, there are numerous effects on the environment and community. For instance, even though right turns at red lights (RTOR) have been implemented as a measure to improve traffic flow and reduce congestion, there are potential environmental effects regarding emissions. Based on one study, RTOR was thought to reduce emissions due to its efficiency, contributing to a 6 percent reduction in vehicle emissions and an improvement in fuel consumption by 4 percent (Lieberman & Cohen, 1976, p. 45). However, the underlying mechanism for vehicle emissions is complicated since there are a variety of factors that influence its rates. Modal shifts, switching from one form of transportation to another, can also help reduce vehicle emissions. As a result, there is a debate about whether RTOR or modal shifts are better for reducing emissions. Although RTOR reduces emissions, there is a greater risk of accidents risking the safety of communities. In turn, this increased risk to pedestrians and cyclists may discourage modal shift.

To measure the impact of RTOR and compare it with modal shifts, there needs to be a comparison of emission rates between each other. Quantifying the emission rates is possible with models, including the Measure and Mobile models. The Measure model observes the effect of signal timing on carbon monoxide emissions while the Mobile model studies the optimization of signal timing to reduce emissions (Coello, Farias, & Rouphail, 2005, p. 324). Both of the models incorporate the mesoscopic traffic model and analyze the movement of vehicles on the street. Through these models, maneuvers such as acceleration, deceleration, idling, and cruising are measured to determine their effects on the environment based on carbon emission rates. By measuring the average rates of carbon emissions at RTOR and comparing them with areas that do not have RTOR, the environmental effects of RTOR can be estimated to decide whether it is beneficial. Different emissions, such as carbon monoxide, nitrogen oxides, and hydrocarbons are key factors that will be measured.

Based on the results of a case study in Lisbon and Cascais that utilized the Measure and Mobile models, areas with optimized signal parameters such as longer green and red lights have fewer emissions and unnecessary stops in comparison to areas with shorter green and red lights. In other words, areas that give drivers more time to react to traffic signals are less accident-prone and more eco-friendly over time. Through this study, effective signal strategies can provide better safety and reduce carbon emissions at intersections with traffic signals. However, RTOR can still be dangerous if drivers are not careful. There needs to be more safety regulations at intersections to give drivers enough time to react and perform maneuvers on the road. Without RTOR, emission rates would be higher based on this study, and there would need to be more usage of modal shifts to counteract the high emission rates.

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 right turn on red may be implemented based on the time of day and/or the 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, “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” (National Association of City Transportation Officials, 2020).

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

Emissions Analysis at Intersection Approaches

As mentioned previously, the permissible "Right Turn on Red" (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), fuel savings also translated into emissions reduction. This section examines more recent literature along with a careful analysis of vehicle trajectories through individual 4-legged signalized intersections to critically examine if those assumptions still hold.

Emissions from ICEV 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.

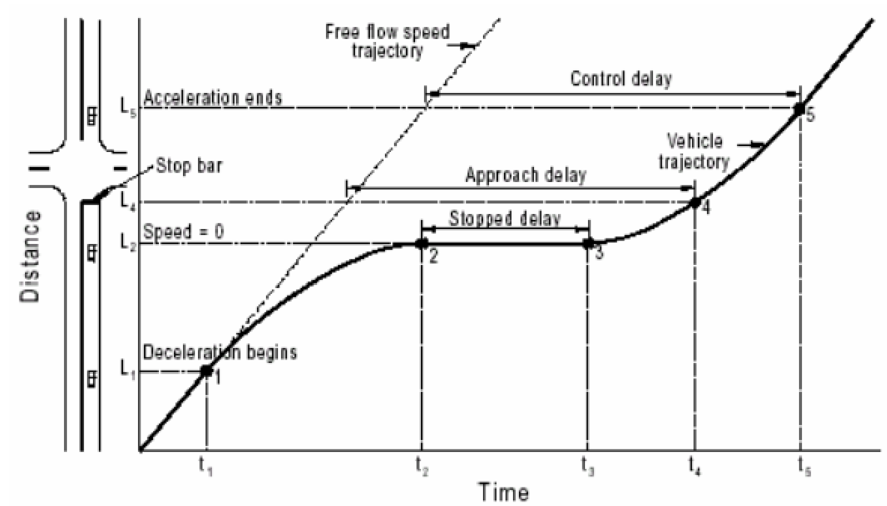

Figure 3. Various Delay Components for Time Spent at Intersection (Darma et al., 2005)

Based on past research including, Darma et al. (2005), Pandian et al. (2009) and Lin et al. (2019), several factors determine the emissions by right turning automobiles at signalized intersections:

- The intersection geometry
  - The turning radius provided 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.
- Nonmotorized travel activity:
  - Number of pedestrians waiting and crossing.
  - Number of bicyclists.
- Surrounding Land-Use
- Enforcement of Traffic Laws

Rouphail et al. (2001) studied empirically the effect of intersection operations on the exhaust emissions of ICEVs. They found that the amount of exhaust emissions does not completely depend on the quantity of control delay. Rather the emissions increase disproportionately during the acceleration episodes. A gradual increase in speed from an idle position will create much less 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, RTOR movements are more emissions-prone than places with RTOR prohibitions, especially in highly conflicting environments (major urban centers) compared to a signal with fewer conflicting traffic (suburban to rural environments). A study by the Connecticut Department of Transportation also found the operational and emissions impact of RTOR restrictions vary widely from intersection to intersection.

A simple methodology to estimate the potential change in emissions following the prohibition of right turns on individual intersections is provided in the Appendix. The Methodology requires the following information for the intersection:

- Conflicting traffic volume
- Right turn traffic volume (queue length)
- Intersection geometry

Since EVs reduce tailpipe emissions to zero, increased adoption of EVs in the state would further reduce emissions benefits even in more suburban environments. Furthermore, given EV acceleration rates are dramatically higher than ICEV, increased EV adoption also makes the case for prohibiting RTOR even stronger from a safety perspective.

Data and Methodology

Data Sources

Several data sources were used for the 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 racial 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.

Additionally, 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 included a place typology, which included seven categories: urban centers (reference), 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 referred 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) as well as 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 jobs accessibility (Frost et al, 2018).

We also used a walkability score from the EPA'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.

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

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
Vehicle	17,480	83	2,092	5

Table 2. Average Annual RTOR Collisions (2011-2022)

	Right-Turn at Intersections		Yield Violations	
	Collisions	**Fatalities**	**Collisions**	**Fatalities**
Pedestrian	851.7	8.2	39.8	0.3 (1 every 3 years)
Cyclist	952.3	3.0	53.8	0.5 (1 every 2 years)
Vehicle	1,456.7	6.9	174.3	0.42

We calculated the number of RTOR collisions in two categories: right turns at intersections and yield violations. We divided the total number of collisions by the total number of years that the dataset represented in order to estimate average RTOR collisions per year. 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.

Overall, the findings are consistent with the literature that documented that RTOR account for about 5 to 15% pedestrian crashes at signalized intersections (Lord, 2002).

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 like 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, in order 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 3 and 4.

Results

The dataset provides descriptive values primarily in the form of proportions, reported in Table 3, 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 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 3. 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

	Cyclist		Pedestrian	
Statistic	Mean	St. Dev.	Mean	St. Dev.
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
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, which failed to yield by 17.6 percent. This relationship underscores the complex interplay between urban design features and collision risks.

Nevertheless, 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 4. 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***
	(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***

	Yield		Right	
Variables	Bicycle	Pedestrian	Bicycle	Pedestrian
	(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
	(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

To better understand the SES results, we plot their predicted values in Figures 4-6. 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.

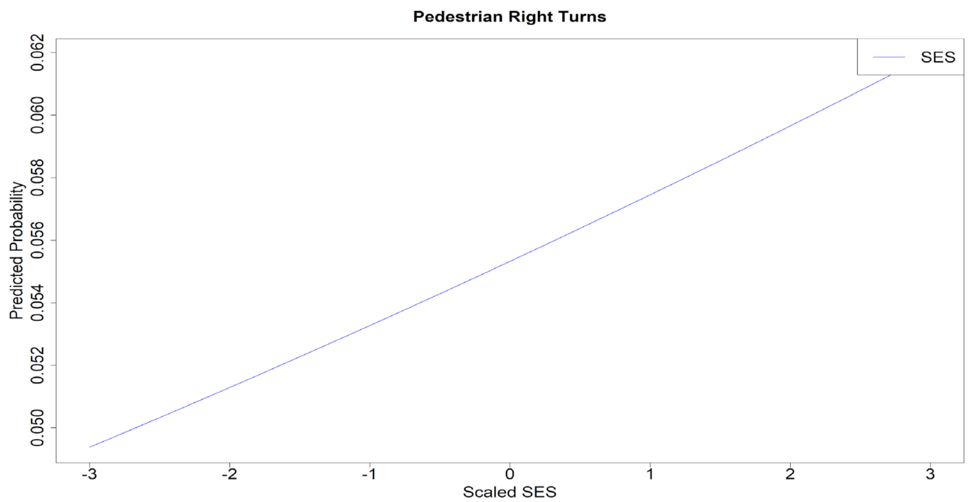

Figure 4. Predicted probability by scaled socioeconomic status for collisions involving a pedestrian in which the driver made a right turn at an intersection before the collision.

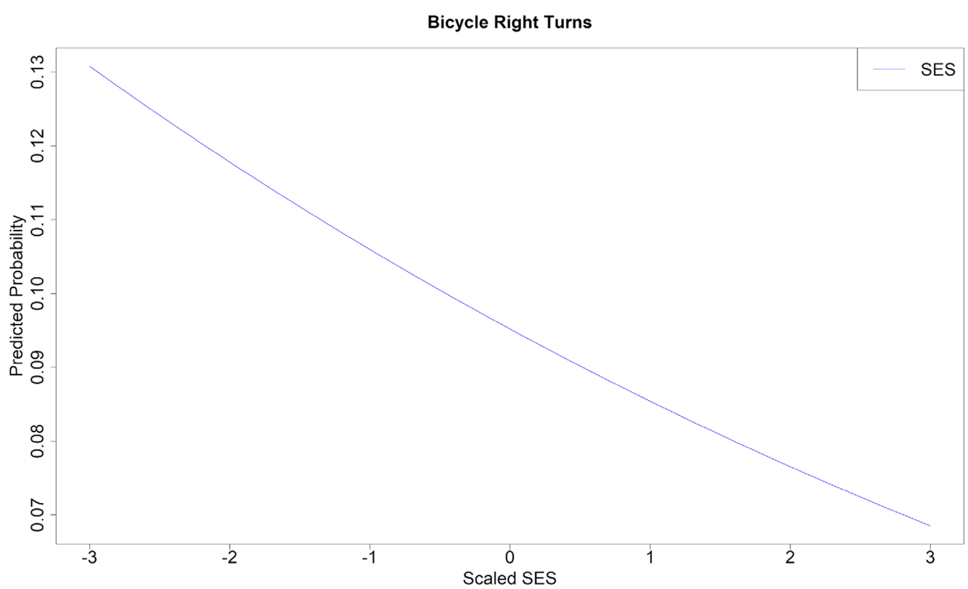

Figure 5. Predicted probability by scaled socioeconomic status for collisions involving a bicyclist in which the driver made a right turn at an intersection before the collision.

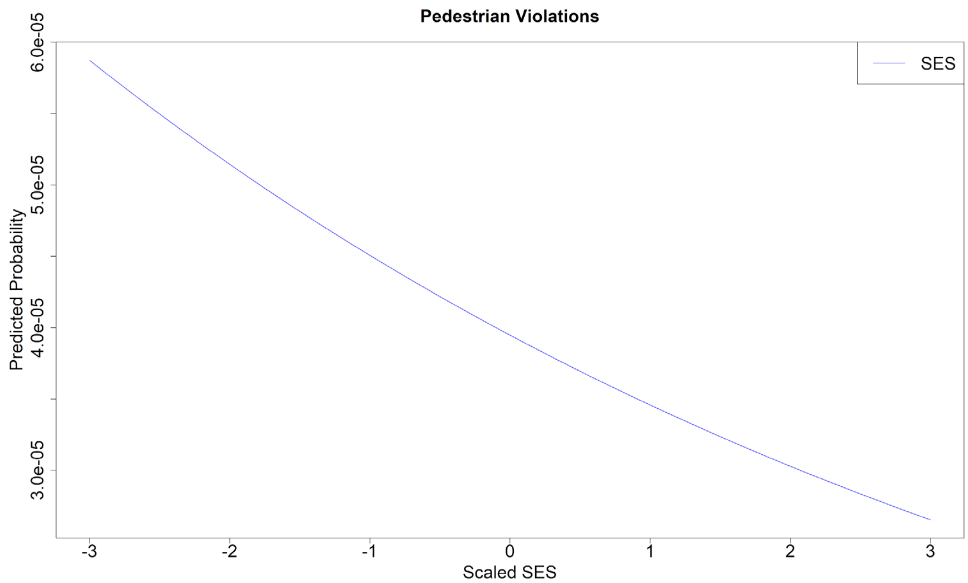

Figure 6. Predicted probability by scaled socioeconomic status for collisions involving a pedestrian in which the driver did not yield.

Intersection Case Studies

Methodology

To identify intersection characteristics that could increase 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, as well as relatively heavy, fast-moving cross traffic. Additionally, several intersections had irregular designs that could add to confusion or distraction amongst drivers.

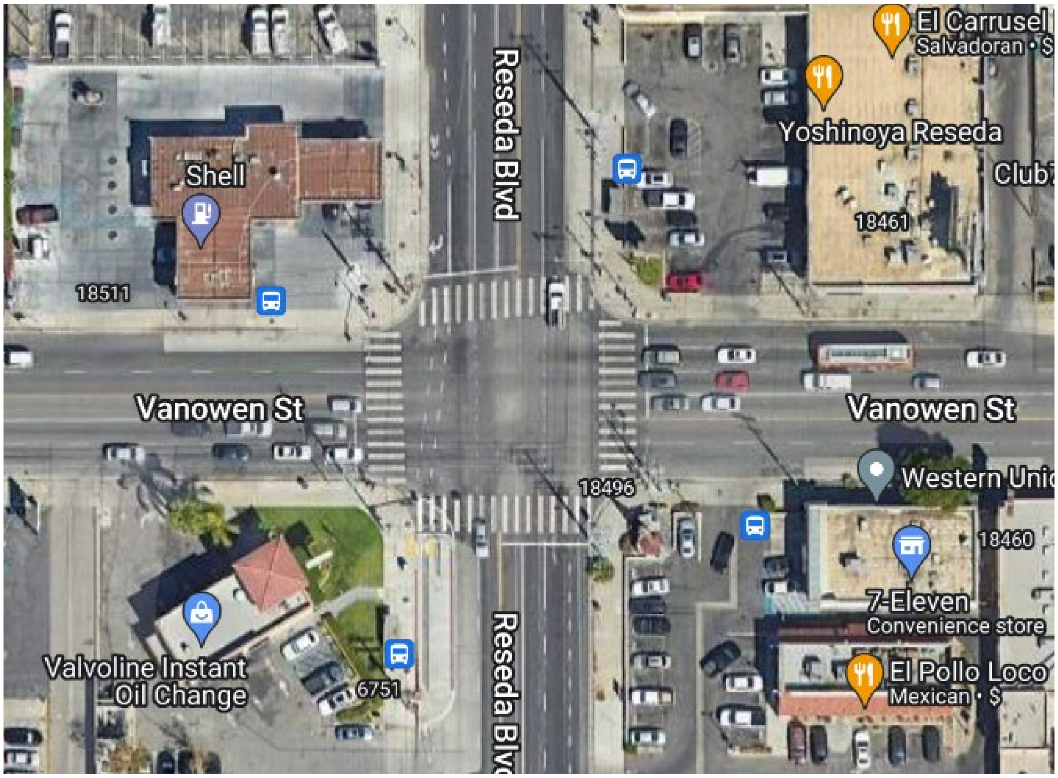

Figure 7. An example of one intersection that had a high number of pedestrian collisions involving right turns at an intersection (6 in 12 years), Vanowen St at Reseda Blvd.

Results and Discussion

This research reviewed RTOR collisions throughout the state and found that right-turn collisions at intersections were responsible for over 39,000 collisions and 217 fatalities (involving pedestrians, bicyclists, and drivers) between 2011-2022. Over half (21,000) of these collisions and 134 fatalities involved a pedestrian or cyclist.

Our crash data analysis along with the literature leads to the conclusion that RTOR movements are generally unsafe for pedestrians, bicyclists, and drivers, damage the livability of our streets for vulnerable road users, while only marginally useful in lowering emissions, and under only certain contexts. Those marginal benefits have declined over the years as ICEV technology has improved and may further decline with increased EV adoption. Furthermore, given the number of conflicts associated with RTOR movements, these movements lower comfort levels for active travelers and livability, and even more so in disadvantaged communities, which have serious implications in terms of physical activity, mental health, and encouraging walking and bicycling which have many climate action benefits. 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).

Existing state law in California, like all states in the country to be sure, requires right turn on red to remain legal at intersections unless a sign prohibiting such maneuvers is posted. Therefore, in most communities, the decision to prohibit RTOR is governed by analysis on a case-by-case basis. SFMTA in their aforementioned July 2023 memo cited the state law as a main barrier to implementing a city-wide ban on RTOR.

"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 the San Francisco's over 1,300 traffic signals." (Olea, 2023).

The relevant guidance is provided by the California Manual on Uniform Traffic Control Devices (MUTCD) SECTION 2B.54. CA MUTCD specifies that "unacceptable number of pedestrian conflicts with right-turn-on-red maneuvers, especially involving children, older pedestrians, or persons with disabilities" is one of the conditions which may be used to prohibit right turn on red at signalized intersections. Communities and agency professionals may use the number of VRUs using an intersection as a stand-in measure for such conflicts. Based on the review of crash data and attempts by communities to address the safety issues resulting from RTOR, this research considered various policy options and provided recommendations in the next section. 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. Under the safe systems approach safety is proactive and safety concerns should be identified and addressed before crashes occur (California Office of Traffic Safety).

We recognize that the decision to ban or allow RTOR movements should consider the specific contexts of the cities and their place types. Therefore, we recommend that state policy should make it easier for California communities to prohibit RTOR movements without necessarily explicitly banning it statewide. The latter would unduly burden communities who want to permit or prohibit RTOR at a vast number of their intersections by default.

Intersection Level Measures: Leading Pedestrian Interval

The introduction of permissive Right Turn on Red (RTOR) in the 1970s has had negative consequences for pedestrian safety. Drivers often focus on traffic from the left, overlooking pedestrians on the right, or they may block intersections while waiting to turn. However, prohibiting RTOR can increase conflicts during Right Turn on Green (RTOG) with concurrent signals (FHWA, 2018). This has prompted consideration of leading pedestrian intervals (LPI). LPIs give pedestrians a head start of three to seven seconds before parallel traffic is allowed to turn right, improving pedestrian safety. LPIs can mitigate this by improving the visibility and safety of pedestrians and other non-motorized users (FHWA, 2018).

Leading pedestrian intervals are a cost-effective method to enhance pedestrian safety and visibility, particularly benefiting elderly individuals and children who may need more time to cross intersections (FHWA, 2009). The Manual on Uniform Traffic Control Devices (MUTCD) provides guidelines on signal timing for LPIs, recommending a minimum duration of 3 seconds to allow pedestrians to establish their presence before traffic is allowed to turn (FHWA, 2018). LPIs have been shown to increase driver-yielding rates, especially in high-traffic areas (Goughnour et al., 2018). The Federal Highway Administration (FHWA) has established criteria for LPI site selection, considering factors like crash history, pedestrian volumes, and areas with vulnerable populations such as school-age children and the elderly (FHWA, 2018).

The North Carolina Department of Transportation (NCDOT) developed a method to analyze design characteristics affecting pedestrians and bicyclists at signalized intersections (Steinman and Hines, 2004). Their study examined features such as crossing distance, roadway space allocation, corner radius dimensions, and traffic signal characteristics, aiming to use the results as a diagnostic tool to enhance safety levels for pedestrians and bicyclists.

Conclusions and Recommendations

In sum, we recommend, that California communities should work towards the prohibition of RTOR movements. The question is, how best to do this, and do this as safely, clearly, and cost-effectively as possible? One of the most fundamental things the state could do is make sure that drivers stop at the red light before proceeding, i.e., ensure that current state law is followed and enforced appropriately. The state could achieve this by encouraging greater police enforcement, coupled with public messaging campaigns. Basically, the state law should make sure everyone at least comes to a full stop before making the right turn at a red light. This may require automated enforcement potentially via the use of red-light cameras. In terms of changes to the existing law the following options may be considered:

California can institute an overall ban of RTOR movements, statewide, unless otherwise signed, which would probably be the safest, clearest, and least confusing policy action to take. In this case, an option could be for cities to select to be an RTOR city and sign at their border and/or select intersections accordingly.

Our analysis of data and literature suggests that banning or permitting RTOR movements should consider the specific contexts of the cities (their place types). 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. Therefore, we recommend that cities be able to determine whether they want to ban RTOR movements or not, and then place signs at their borders and then at intersections according to whether it is permitted or not, based on their specific contextual factors of the types of places and intersections they have and want to be. Nevertheless, the clearest, safest action to take would be to have a statewide ban on RTOR movements, unless otherwise signed at the city borders and/or intersections. Public Service Announcement (PSA) campaigns should also accompany these policy changes.

Rather than trying to prohibit (or permit) RTOR movements on an intersection-by-intersection basis, 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.** Cities adopting blanket prohibition under this state law change should be required to have LPI implemented at all signalized intersections. 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, as well as proximity of transit stations.

Another option would 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.

With any of these approaches, 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 congestion and energy-saving effects, the State of California should work towards modifying, limiting, and/or banning RTOR practices.

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Appendix A

There are potentially five different conflicting movements for the automobile making a right turn on red maneuver on a 4-legged signalized intersection. Two of these are pedestrian crossing movements, one is from bicycle traffic running parallel to traffic movement. Also, there are two conflicting automobile movements, one 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 a right turning traffic thus can be expressed as equation 1.

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

(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.