Effects of Bike Lane Implementation on Traffic Accidents: Evidence for the City of Recife, Brazil *

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Abstract

We use the recent expansion of bike lanes in Recife City (Brazil) to identify the causal impact of bike lane implementation on different kinds of traffic accidents in the city, including crashes involving automobiles, bikes, motorcycles, victims, and fatalities. The identification of such a causal effect is carried out using the multiple-period difference-in-differences estimator suggested by Callaway and Sant'Anna (2021) applied to geocoded traffic accident data and the implementation of cycle paths information provided by Recife City Hall. Our main results indicate that, between 2016 and 2022, treated areas had, on average, 2.5 fewer accidents (4.5 fewer for automobile crashes and 0.5 fewer for motorcycle crashes) than untreated areas for every 100 crashes each quarter. As time passes, the reduction in accidents due to bike lane implementation becomes more evident, although its significance decreases after the 12th quarter of exposure. Conversely, our results indicate that the policy does not affect reducing cyclist, pedestrian, victim, or fatality crashes. Finally, our findings highlight the importance of incorporating safety-based incentives in urban planning and infrastructure projects to mitigate traffic accidents.

Keywords: Bike Lane, Traffic Accidents, Difference-in-Differences

JEL Codes: R4, Q58

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1 Introduction

Every year, around 1.19 million people die from road traffic accidents, with an additional 20 to 50 million suffering non-fatal injuries, many resulting in disability. Low- and middle-income countries, despite having only 60% of the world's vehicles, account for 92% of these fatalities (WHO, 2023). In the context of the sharp increase in the number of motor vehicles in developing countries, policies have been rolled out to mitigate traffic accidents and to encourage making non-motorized transportation a priority. Evidence shows that enforced speed limits reduce vehicle speeds and the number of accidents (Archer et al., 2008; Ang, Christensen, and Vieira, 2020). Likewise, bike lanes might help to reduce the number of crashes tackling mixed traffic issue (Nolan, Sinclair, and Savage, 2021) slowing down automobile speeds, thereby likely reducing the risk of potential accidents (Pucher and Buehler, 2017). Nonetheless, there is no causal evidence about whether bike lane implementation leads to diminished overall traffic accidents.

In this paper, we consider the remarkable 310% increase in the cycling network between 2016-1 and 2022-4 in Recife City, Brazil, to assess the effects of bike lanes on traffic accidents. This bike lane network expansion was provided by the state government and Recife City Hall, and it was formally launched in 2012. However, only after some years did the program take off. The program called *PEDALA* aims to promote bicycling as a mode of transportation, implementing connections between various public facilities, including parks, squares, public markets, and bus terminals in the City of Recife. Thus, we aim to estimate the dynamic average treatment effect on treated regions (regions with bike lanes) through a difference-in-differences approach with multiple time periods (Callaway and Sant'Anna, 2021). In other words, we evaluate the dynamic effects of bike lane implementation on accident outcomes (aggregated crashes and disaggregated crashes involving automobiles, bikes, motorcycles, victims, and fatalities).

Our results indicate the staggered rollout of the bike lanes contributed to a general decrease in traffic accidents in the city, particularly in the context of crashes involving automobiles and motorcycles. Between 2016 and 2022, treated areas had on average 2.5 fewer accidents (4.5 fewer for automobile crashes and 0.5 fewer for motorcycle crashes) than untreated areas for every 100 crashes each quarter. While the impact on traffic accidents may not seem pronounced, it remains relatively consistent over time. As time elapses, the reduction in accidents due to the bike lane implementation becomes more evident, although its significance wanes after the 12th quarter of exposure to the treatment. On the other hand, our results indicate no effect of the policy in reducing cyclist crashes. These results consider fixed and time fixed effects and covariates known in the literature to influence traffic accidents. The main results are also consistent after considering different robustness checks.

The paper contributes to a wide-growing body of literature that has been focused on investigating road infrastructure policies' effects on traffic accidents. Ang, Christensen, and Vieira (2020) evaluates a speed limit reduction program in São Paulo, Brazil using a dynamic event study design and measurements of 125 thousand traffic accidents. They find that the program resulted in 1889 averted accidents within the first 3 quarters and reduced accidents by 21.7% on treated roads. Additionally, Alves, Emanuel, and R. H. Pereira (2021) examines the causal effect of highway concessions on road safety outcomes using daily data from Brazilian Federal highways over 11 years between 2007 and 2017. They find that concessions promote a small but significant reduction in the number and fatality of road crashes as well as the number of people and vehicles involved in crashes.

Particularly, several studies are focused on investigating the relationship between bike lanes and cyclist safety (Schepers et al., 2017; Nolan, Sinclair, and Savage, 2021; Nanayakkara et al., 2022), but little is known if bicycle paths also might reduce general traffic accidents. Our paper addresses this issue filling out the literature lack not just concerning bike crashes, but also regarding general traffic accidents (crashes involving motor vehicles and pedestrians). When drivers pass cyclists on roads with painted bike lanes, they tend to give more space than on roads without bike lanes (mixed traffic). This is true even when controlling for the space available on the roadway (Nolan, Sinclair, and Savage, 2021). Conversely, the bike lanes effect has opposite directions when we observe only crashes involving bikes: higher safety with dedicated bike lanes reducing bike traffic accidents (Nolan, Sinclair, and Savage, 2021), but a higher number of cyclists due to the bike lanes implementation increasing the probability of accidents involving bikes (Wei and Lovegrove, 2012; Hamann and Peek-Asa, 2013).

The remainder of the paper is organized as follows. In section 2, we provide the background of the Recife City bike lane expansion and traffic accidents. In section 3, we present the data and, in section 4, we describe the identification strategy. In sections 5 and 6, we display and discuss the results and robustness checks, respectively. Finally, in section 7, we present the concluding remarks of the research.

2 Background: Bike lanes rollout and traffic accidents in Recife

In developing countries, the absence of transport infrastructure, particularly safe paths for bicycle use, contributes significantly to road traffic accidents, imposing a substantial social and economic toll. Brazil exemplifies this issue, registering only 8% of its population using bicycles as a mode of transportation, trailing behind other South American countries such as Colombia (17%), Argentina (16%), Chile (13%), and Peru (12%). Compounding this problem, the number of motor vehicles in Brazil increased by approximately 142% from 2006 to 2022 (IBGE, 2022).

In this chaotic context, many cities have aimed to improve urban traffic. Following the trend, since a significant share of the Recife population (13%) commute to work by bike, the state government launched the program *PEDALA PE* in 2012 as part of a set of mobility interventions in the Metropolitan Region of Recife which aimed to improve public transport and traffic in general, promoting their integration, harmonious and peaceful coexistence through a program of mobility created in 2010 called *Programa Estadual de Mobilidade* (PROMOB) (Estado de Pernambuco, 2013).

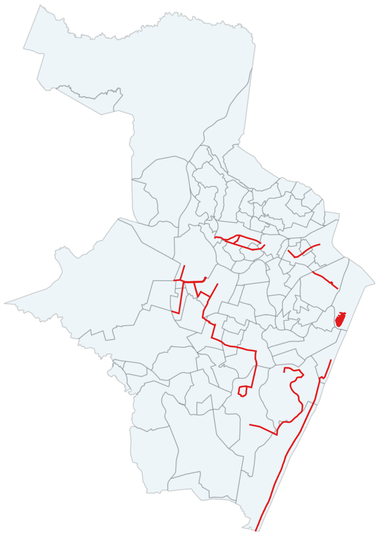
In turn, the *PEDALA PE* program has emerged as a supportive tool for promoting bicycling as a mode of transportation. This initiative encompasses a range of structural and educational measures aimed at fostering the use of bicycles and integrating them with other modes of transportation. In terms of structural initiatives, Recife City has significantly expanded its bike lane network, with a focus on neighborhoods housing key public facilities like parks, squares, public markets, and bus terminals. This strategic approach creates connectivity points among these facilities, enhancing the overall accessibility of the bicycle infrastructure (Estado de Pernambuco, 2013).

According to Recife City Hall data, the initial implementation of bike lanes began in 2004, covering an extension of 7.85 km. However, the bike lane expansion did not spread sharply, as evidenced by the fact that, at the beginning of 2016, the total extension of bike lanes had only reached 42.63 km (Cidade do Recife, 2023). A similar Northeastern capital city, Fortaleza, for example, had reached 68 km of bike lane extension in 2012 (in 2023, 283 km of bike lane extension) (Fortaleza, 2023).

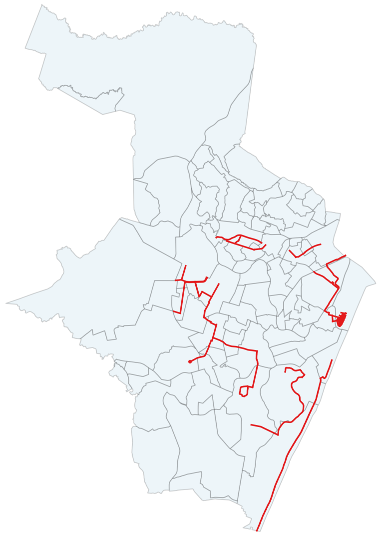
Nevertheless, despite years of relatively weak expansion, Recife intensified its bike lane implementation planning and accomplished a substantial expansion of bike lanes in Recife over time, depicted in Figure 1 through four panels from 2016-1 to 2022-4. Notably, the bike lane expansion gains momentum from 2019/2020 onwards. It is noteworthy that the total extension of bike lanes increased by only 7 km from 2016-1 (42.63 km) to 2018-1 (49.63 km). However, in the subsequent two panels (c and d), bike lanes experienced significant growth, reaching 116.03 km in 2020-1 and 174.73 km in 2022-4, respectively (Cidade do Recife, 2023).

In turn, Figure 2 presents the logarithm of the number of accidents in Recife City aggregated by year-quarterly from 2016-1 to 2022-4. The red line represents registered accidents, including collisions and running-over incidents, documented by traffic authorities. Meanwhile, the green line denotes the count of cars involved in these incidents. It's worth noting that during certain periods, the number of cars involved exceeds the total number of accidents, suggesting multiple-vehicle incidents were prevalent. Additionally, the yellow line depicts accidents involving bicycles, while the remaining lines imply incidents resulting in victims (injuries), fatalities (deaths), and those involving motorcycles, represented by purple, light blue, and dark blue lines, respectively.

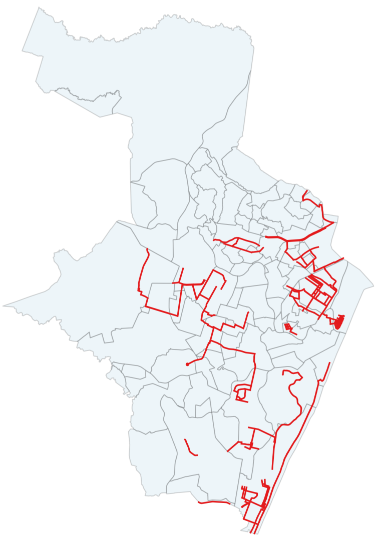
Furthermore, a pronounced decrease in overall accident occurrences is evident from 2019-4 to 2020-1, particularly concerning incidents involving at least one car. This notable reduction coincided with the onset of the COVID-19 pandemic, resulting in reduced vehicular traffic on roadways. However, it is essential to acknowledge that other contributing factors may have influenced this decline, as accident numbers remained relatively low even after traffic patterns returned to normal after the initial pandemic shock. Nonetheless, it's worth highlighting that bicycle-related crashes exhibited an upward trajectory, with fatalities returning to pre-pandemic levels by 2022-4. Thus, the observed patterns vary across these types of accidents.



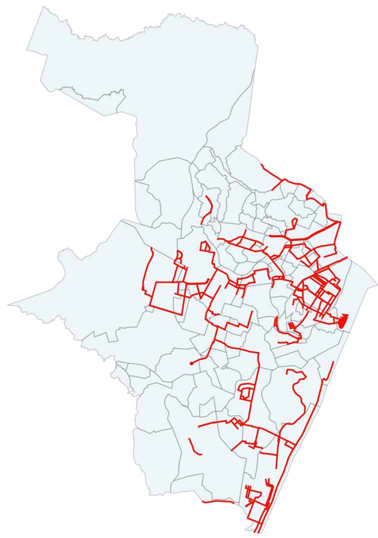
(a) 2016-1



(b) 2018-1



(c) 2020-1



(d) 2022-4

Figure 1: Recife City Bike Lane Expansion
Notes: Elaboration by the Author. Database from Recife City Hall.

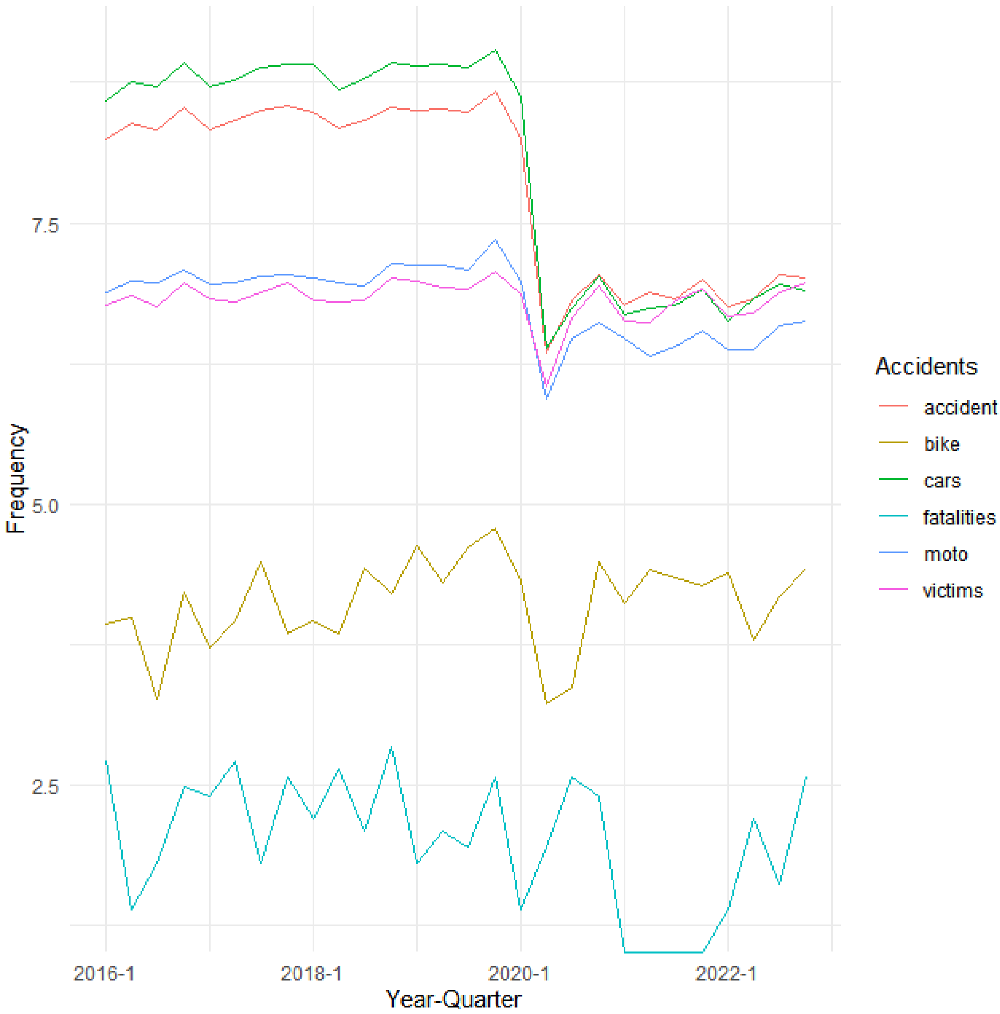


Figure 2: Number of Accidents in Recife City
Notes: Elaboration by the Author. Database from Recife City Hall.

3 Data

Using data from Recife City Hall available on *Recife Dados* (Recife Data) website, we integrated two datasets, *Acidentes de Trânsito* and *Malha Cicloviária do Recife* (Traffic Accidents and Recife Cycle Path Network), containing information on detailed accidents and bike lanes. We aggregate it over 28 quarterly periods, from 2016-1 to 2022-4. The dataset includes details about accident localization, day and time, crash types (collision, running over, and others), involved vehicles and pedestrians, and whether the incident resulted in victims or fatalities. Concerning bike lane implementation information, the dataset incorporates details on bike lane localization and the period of initiation for each bike lane.

In addition, based on the H3 index developed by Brodsky (2018), we covered all of Recife City territory with 1,826 hexagons and defined them as units of analysis. This hexagonal hierarchical geospatial indexing system is close to the number of Recife 2010 census tracts and enables a range of algorithms and optimizations based on the grid, including nearest neighbors, and shortest path, which we might use to identify indirect effects and robustness checks forward (Brodsky, 2018).

Each hexagon has an area of 0,11 km^2, approximately a city block, that allows a detailed spatial analysis because we can use the spatial distribution of urban accessibility for the regions with relevant information about modes of transport (walking, cycling, public transport, and car), times of day (peak and off-peak), population groups (according to levels of income, color, sex and age), soil use, and types of activity (jobs, schools, health services and social assistance centers) (R. H. M. Pereira, Braga, et al., 2022; R. H. M. Pereira, Herszenhut, et al., 2022; R. H. Pereira and Herszenhut, 2023). This way, the final dataset assigns for each identified hexagon information about accidents and if some bike lane is within and intercepts its limits.

By the way, appropriately defining treated hexagons and control hexagons presents our primary potential challenge. To address this, we use a restricted sample that includes only areas designated to receive a bike lane network. Figure 3 shows the treated hexagons and never treated hexagons. Hexagons intersected by a bike lane are classified as treated (red hexagons), while the control group (never treated) consists of hexagons that will only receive treatment in 2023 (blue hexagons). Since our analysis covers the period from 2016 to 2022, the hexagons scheduled for treatment in 2023 serve as a suitable counterfactual, as they are considered untreated within our study period. This approach ensures the best possible counterfactual for our estimations, helping to mitigate potential endogeneity in the selection process of regions eligible for the bike lane network expansion.

Table 1 exhibits the mean and the standard deviation for control and treated hexagons of accident types, some characteristics such as number of residents, income, number of public schools, formal jobs, healthcare facilities, and school enrolments. It also displays travel time from the closest public school and healthcare facility and accessibility. It is noteworthy that control refers to those hexagons never treated. These hexagons will be treated in 2023, but until the last period of our data, they never received a bike lane network.

In this data, the means of key variables between treated and control hexagons are highly similar, including average household income per capita, the number of formal jobs, and distances to healthcare facilities and formal jobs. Although our focus has been concentrated on the parallel trend assumption, these similarities between treated and control reinforce the validity of this approach.

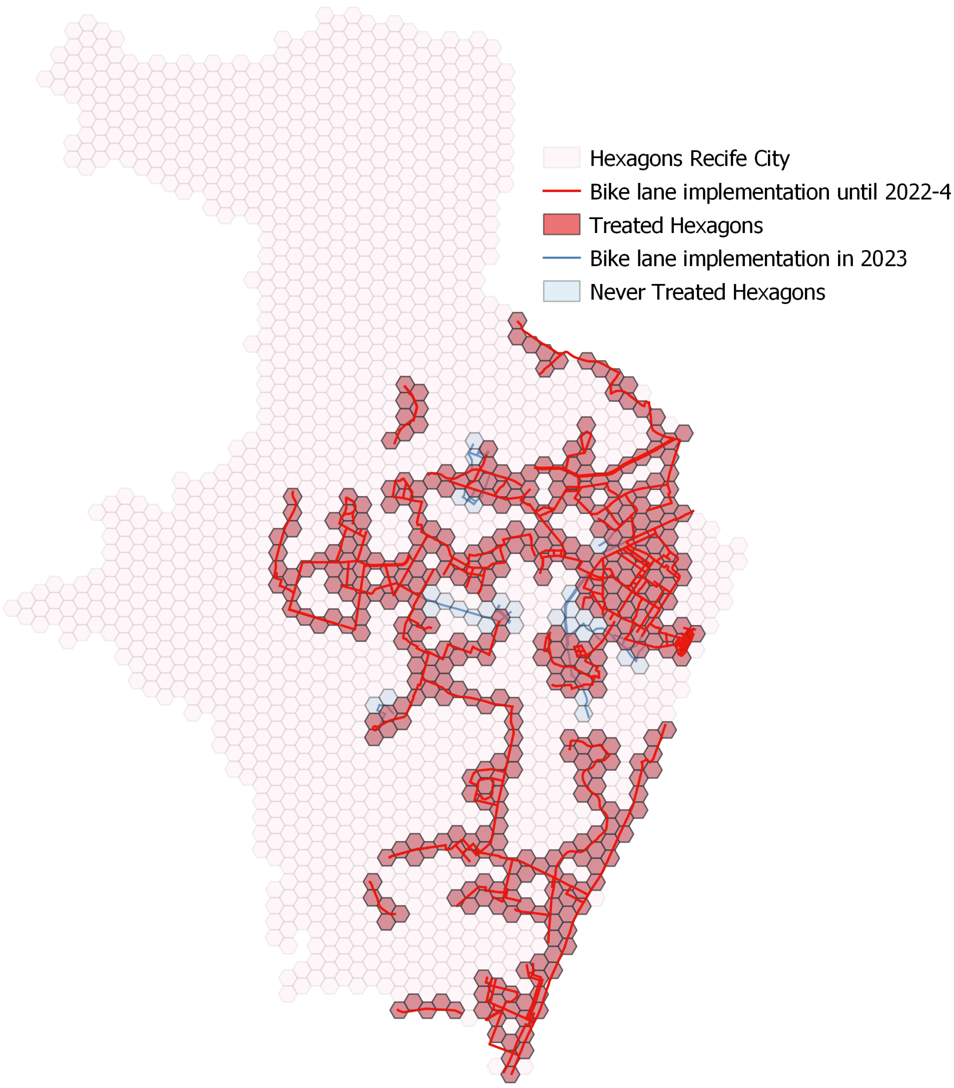


Figure 3: Treated and Never Treated Hexagons
Notes: Elaboration by the Author. Database from Recife City Hall.

Additionally, Figure 4 illustrates the average number of accidents per year/quarter in both treated and control hexagon areas. Panels (a) and (b) demonstrate a similar trend. The decrease in the average number of accidents, particularly those involving at least one automobile and one motorcycle, is more noticeable in treated areas. However, for other panels (accidents involving cyclists, victims, and fatalities), the patterns are quite similar, with no clear indication emerging. Nevertheless, untreated areas generally show a lower incidence of crashes in these cases.

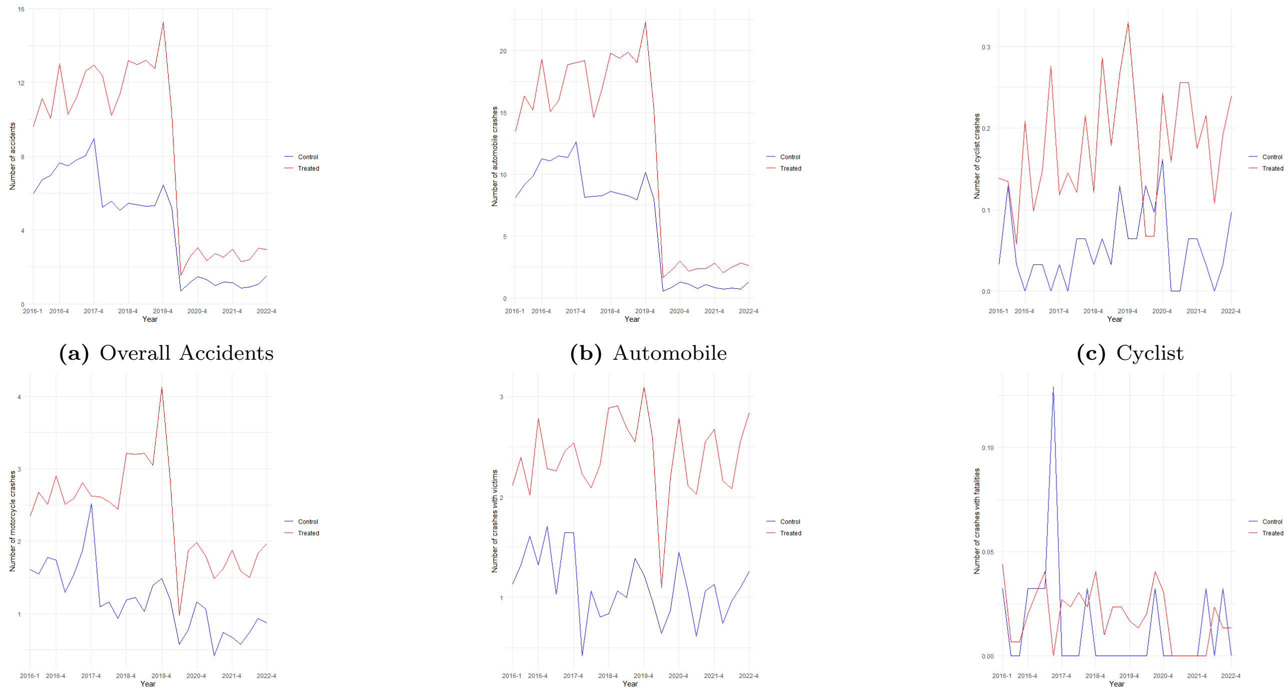
Table 1 - Summary Statistics (Baseline)

	Mean		SD	
	Control	Treated	Control	Treated
Accident types				
All accidents	4.33	8.25	9.84	23.59
Automobiles	6.12	11.66	14.89	35.58
Cyclist	0.05	0.18	0.23	1.22
Victims	1.11	2.40	2.23	6.10
Fatalities	0.01	0.02	0.13	0.26
Characteristics				
Residents	1091.68	1393.66	820.02	914.26
Average household income pc	1242.85	1265.52	835.31	1050.07
Number of public schools	0.35	0.43	0.79	0.78
Number of formal jobs	796.52	640.70	762.94	995.32
Formal jobs with 1st education	122.19	109.00	118.38	153.17
Formal jobs with 2nd education	509.10	391.07	486.86	607.31
Formal jobs with 3rd education	165.23	140.62	215.55	320.63
Number of healthcare facilities	0.68	0.35	1.06	0.69
Number of school enrollments	143.55	268.99	332.01	1838.33
Travel time from to the closest				
Public school	10.50	9.38	4.10	4.37
Healthcare facility	9.16	9.88	3.83	4.46
Facilities accessible within n minutes				
Public schools 15 min	4.81	4.39	3.70	3.24
Public schools 30 min	35.39	26.60	13.69	12.85
Healthcare 15 min	8.32	3.58	8.73	4.11
Healthcare 30 min	41.68	22.94	22.83	19.69
Formal jobs 15 min	12701.42	7258.86	11103.42	7371.46
Formal jobs 30 min	70488.81	42731.72	42658.58	32627.04

4 Identification Strategy

Following the staggered implementation process, we employ a staggered difference-in-differences methodology with multiple time periods to evaluate pre-treatment and post-treatment effects proposed by Callaway and Sant'Anna (2021). We report the intervals with 95% confidence, and the errors are clustered by the hexagon level. Their estimators yield non-parametric identification results, leading to a doubly robust estimation method. This allows applied researchers to better leverage variation in treatment timing and to elucidate treatment effect heterogeneity across different dimensions.

In this manner, we address the potential bias arising from treatment effects that vary over time and appropriately handle comparisons between early and late treatment groups. Our approach implies that our estimates are not significantly influenced by the biases inherent in difference-in-differences strategies when time-varying effects (De Chaisemartin and



(a) Overall Accidents **(b)** Automobile **(c)** Cyclist

(d) Motorcycle **(e)** Victims **(f)** Fatalities

Figure 4: Average of Accidents per Year/Quarterly (Treated and Control areas). Notes: Elaboration by the Author. Database from Recife City Hall.

d'Haultfoeuille, 2020; Goodman-Bacon, 2021).

In our baseline analysis, the control group consists of hexagons classified as "never treated," meaning they are areas that do not receive treatment at any point in the study period. This group remains constant across different groups and periods. As an alternative, we also consider a "not yet treated" control group, which will be discussed in the robustness checks section. In this case, the control group includes hexagons that have not yet received treatment during the specified period. This category encompasses all "never treated" hexagons, as well as additional hexagons that will eventually receive treatment but have not yet done so during the period under analysis.

Specifically, the average treatment effect is calculated for hexagons within a specific group 'g' at a particular time period 't,' as denoted by:

$$ATT(g,t) = E[Y_t(g) - Y_t(0)|G_g = 1] \tag{1}$$

This represents the causal parameter known as the group-time average treatment effect. In simpler terms, it signifies the average impact when a hexagonal area in group 'g' receives a bike lane. It is important to note that, for the sake of simplicity, we are assuming uniform treatment effects across all groups. Additionally, within this framework, hexagons are assumed not to anticipate their treatment status, thereby satisfying the no-anticipation assumption. Furthermore, these estimates can be aggregated to provide an overall estimator. An overall indicator of treatment effect, which considers weighted aggregation, can be obtained by:

$$\theta^{all} = \left(\frac{1}{k}\right) \sum_{g=2} \sum_{t=2}^{T} \mathbf{1}\{t \geq g\} ATT(g,t) P(G=g|G \leq T). \tag{2}$$

where $k = \sum_{g=2} \sum_{t=2}^{T} \mathbf{1}\{t \geq g\} P(G=g|G \leq T)$ and $P(G=g|G \leq T)$ measures the weight of treatment cohort g in the total.

Furthermore, to summarize the bike lane implementation effect for periods of exposure, we aggregate all group-time average treatment parameters by years after the treatment shock. Since we aim to estimate the dynamic average effect of bike lane implementation, we measure the effects of a hexagon unit participating in the treatment at different lengths of exposure to the treatment for exactly e time periods:

$$\theta_D(e) := \sum_{g=2}^{\tau} \mathbf{1} g + e \leq \tau ATT(g, g+e) P(G=g|G+e \leq \tau). \tag{3}$$

5 Results

5.1 General results

We begin by presenting the general results for our preliminary outcomes related to traffic accidents. Table 1 shows a single parameter for the average treatment effect on the treated (ATT) for three outcome variables related to traffic accidents. All estimates control for hexagon (region) and quarter (time) fixed effects (denoted as "Hex. FE" and "Quarter FE," respectively), ensuring that the results account for variations over time and across different geographic areas. In column 1, the estimate for the average causal effect on overall accidents is -7.6, which is statistically significant at the 1% level. In other words, given the average of 300 crashes per quarter between 2016 and 2022, treated hexagons had, on average, 2.5 fewer accidents than untreated hexagons for every 100 crashes each quarter. Conversely, columns (2) and (3) show that the average effect on treated hexagons for accidents with victims (injuries) and fatalities (deaths), respectively, are not statistically significant.

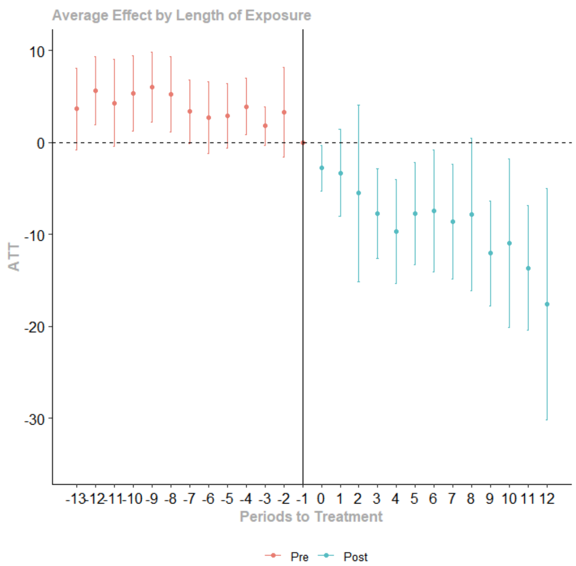
Table 1 - Overall Effects of Bike Lanes Implementation

	Dependent variable		
	Accidents (1)	Victims (2)	Fatalities (3)
Bike lane Implementation	-7.635^{***}	-0.376	-0.118
	(1.6249)	(0.7856)	(0.075)
Hexagon Fixed-Effects	Yes	Yes	Yes
Quarter Fixed-Effects	Yes	Yes	Yes
No. of Hex.	326	326	326
Obs	8,525	8,525	8,525

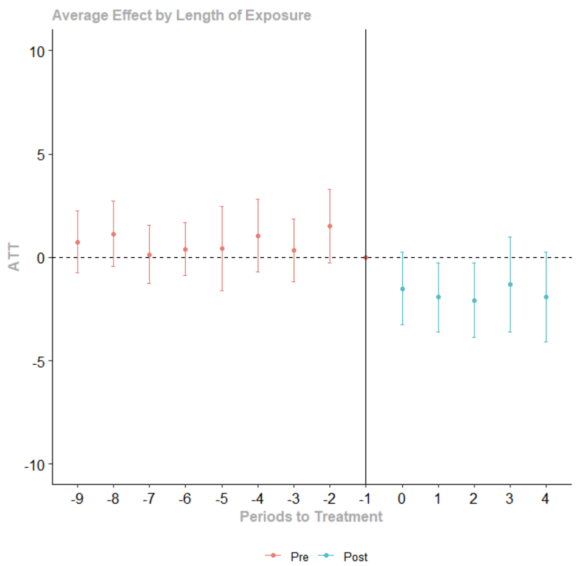
Note: Standard errors are in parentheses and clustered at the hexagon level. *p<0.1; **p<0.05; ***p<0.01.

Regarding the dynamic effects, Figure 5 illustrates the compilation of group-time average treatment effects estimated using an event study approach with dynamic difference-in-differences across multiple time periods, as outlined by Callaway and Sant'Anna (2021). In all panels, event time 0 corresponds to the immediate impact effect (first blue dot), and event time -1 represents the effect in the quarter before a hexagon area received the treatment. Similarly, event time 1 represents the effect in the immediate quarter after a hexagon area received the bike lane. We defined the treated groups g according to the quarter in which the hexagons received the bike lane, and we defined our baseline as the quarter before treatment, $t-1$. This means that all differences are relative to a particular period, and, most commonly, it is set to be the period immediately before the treatment starts.

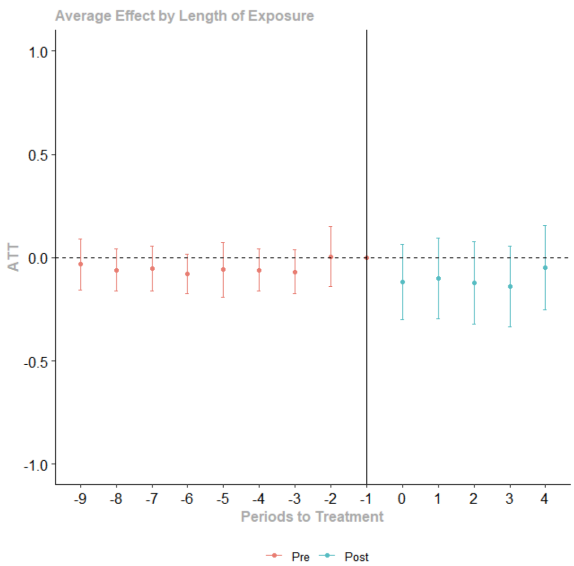
The panels display the event-study results from the estimation using a control group consisting of hexagons that were never treated until the fourth quarter of 2022. These hexagons are slated to receive the bike lane network in 2023 and the first quarter of 2024. Consequently, they serve as our best counterfactual because these "never treated" regions share similar regional backgrounds, making them potential candidates for future treatment. This reinforces the idea of treatment assignment being "as good as random". This group does not change across groups or time periods. Panel (a) highlights the average impact of bike lane implementation over time. As time progresses, the reduction in accidents due to bike lane implementation becomes increasingly evident, but its significance diminishes after the 12th quarter of exposure to the treatment. Panel (b) shows statistically significant effects, with a reduction of 2 accidents with injuries for periods 1 and 2. Finally, panel (c) does not show significance at the 5% level for accidents involving fatalities. Moreover, all panels appear to hold the hypothesis of parallel trends during the pre-treatment period (before g=0).



(a) General Accidents



(b) Victims



(c) Fatalities

Figure 5: Event study: Effect of bike lane exposure on accidents, victims and fatalities.

5.2 Different kinds of traffic-accidents

The different modes of transport and circulation in the city, as they involve different needs for space, speed, and safety conditions, can be affected differently by cycle paths. We now investigate this possibility by considering the impact of bike lane expansion on traffic accidents by different transport modes.

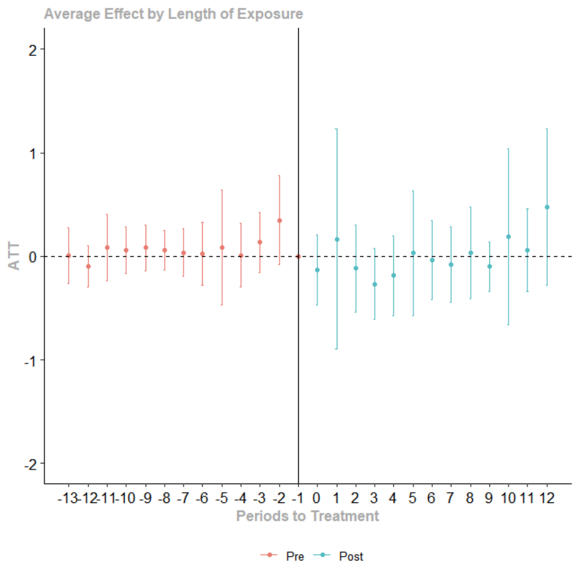
The new set of estimates is presented in Table 2, which displays the overall estimates of the average treatment effect on the treated (ATT). Notice that all estimates are controlled for the hexagon (region) and quarter (time) fixed effects. In column 1, the estimate for the average causal effect on overall accidents is -13.34, which is statistically significant at the 1% level. This implies that the effect of bike lanes on accidents involving at least one automobile is almost double the effect on general accidents. Treated hexagons had, on average, 4.5 fewer accidents than untreated hexagons for every 100 crashes each quarter. Furthermore, in column 3, we find statistically significant effects on accidents involving at least one motorcycle. However, the effect is nine times lower than in cases involving automobiles (column 1). On the other hand, columns (2) and (4) do not show statistically significant estimates for accidents involving cyclists and pedestrians, respectively. The specific case of bike accidents will be discussed in the forthcoming event study.

Table 2 - Overall Effects of Bike Lanes Implementation - Different kinds of traffic accidents

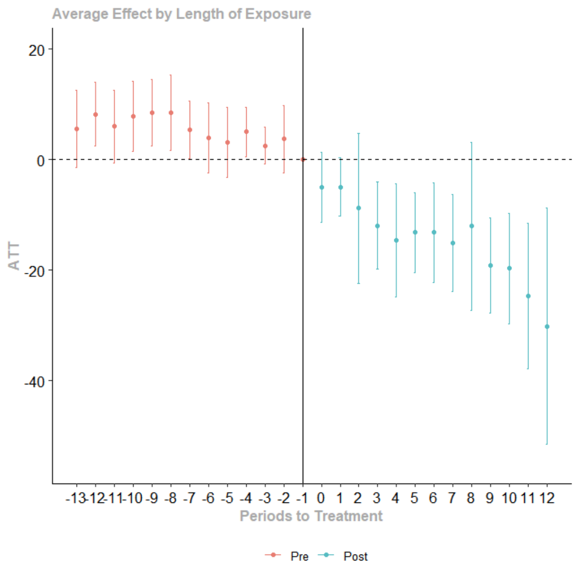
	Dependent variable			
	Automobiles (1)	Cyclist (2)	Motorcycle (3)	Pedestrian (4)
Bike lane Implementation	-13.341^{***}	-0.048	-1.378^{***}	-0.257
	(3.242)	(0.141)	(0.520)	(0.222)
Hexagon Fixed-Effects	Yes	Yes	Yes	Yes
Quarter Fixed-Effects	Yes	Yes	Yes	Yes
No. of Hex.	326	326	326	326
Obs	8,525	8,525	8,525	8,525

Note: Standard errors are in parentheses and clustered at the hexagon level. *p<0.1; **p<0.05; ***p<0.01.

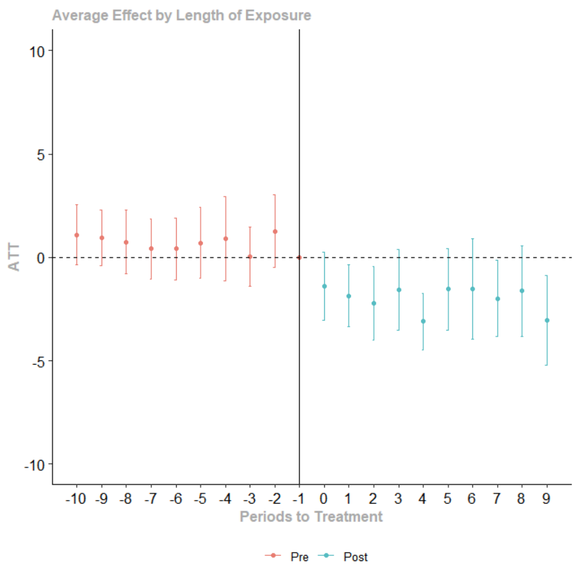
In addition, Figure 6 presents four panels, each corresponding to a different accident outcome variable. Panel (a) indicates that, despite being designed for cyclists, bike lanes do not significantly reduce bike crashes. While bike lanes can separate cyclists from motor vehicle traffic, thereby reducing accidents, they also encourage more people to cycle, potentially increasing the number of bicycle accidents. In contrast, panel (b) shows that automobile crashes are sensitive to bike lane implementation, following a pattern similar to the general accident event study in Figure 5. Panel (c) demonstrates statistically significant reductions in motorcycle accidents for certain periods (1, 2, 4, 7, and 9 after the treatment). Lastly, panel (d) does not show significant effects at the 5% level for pedestrian accidents.



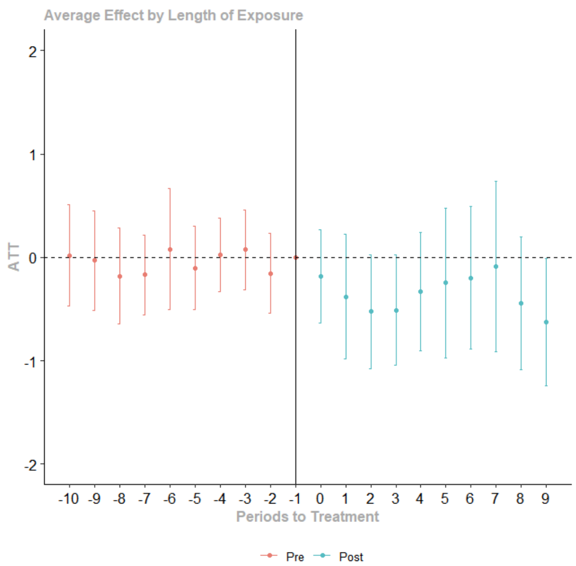
(a) Cyclist



(b) Automobile



(c) Motorcycle



(d) Pedestrian

Figure 6: Event study: Effect of bike lane exposure on different kinds of traffic-accident.

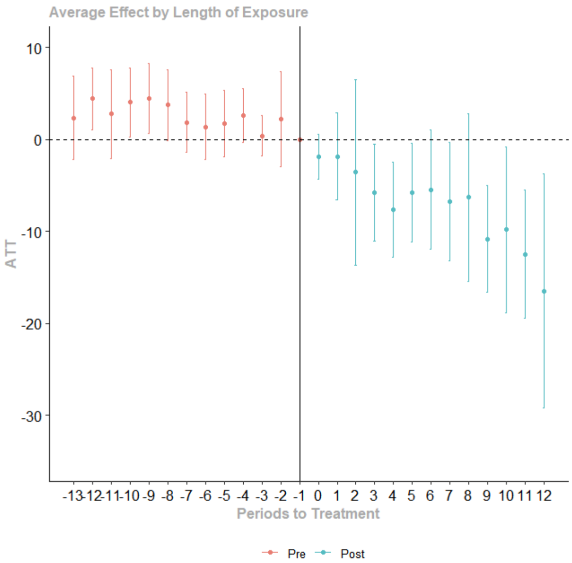
6 Robustness checks

6.1 Alternative control group

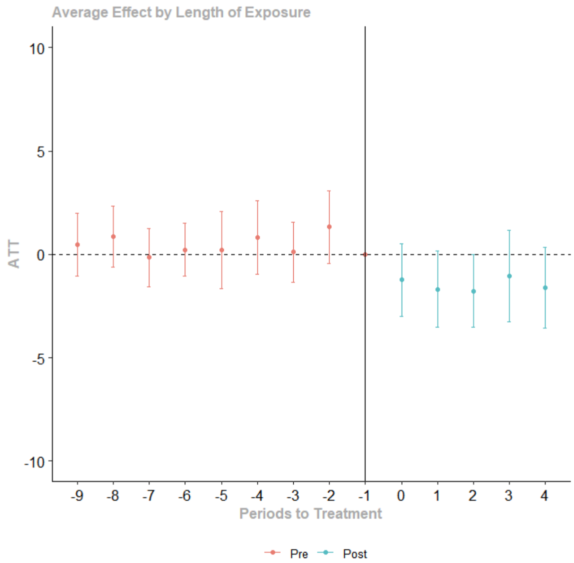
Our first robustness exercise selects alternative control groups. Callaway and Sant'Anna (2021) suggest another option for the control group is to use the "not yet treated". The "not yet treated" include the never treated as well as those units that, for a particular point in time, have not been treated yet (though they eventually become treated). This group is at least as large as the never treated group though it changes across time periods. In our case, the control group is set to the group of hexagons that have not yet received a bike lane implementation in that time period. This includes all never treated hexagons, but it includes additional hexagons that eventually receive a bike lane implementation, but have not received yet.

Figure 7 shows panels containing the event-study results for general accidents, victims, and fatalities from the alternative control group: "not yet treated". All panels in Figure 7 provide similar dynamic effects compared to the baseline results. Panel (a) shows that the reduction in accidents due to bike lane implementation is statistically significant only from the fourth quarter of intervention. The negative effect on general accidents becomes stronger, on average, until the twelfth quarter of exposure to the treatment. In contrast, panels (b) and (c) do not show statistically significant effects at the 5% level for victims and fatalities. As with our baseline results, all panels in Figure 7 uphold the hypothesis of parallel trends during the pre-treatment period (before g=0).

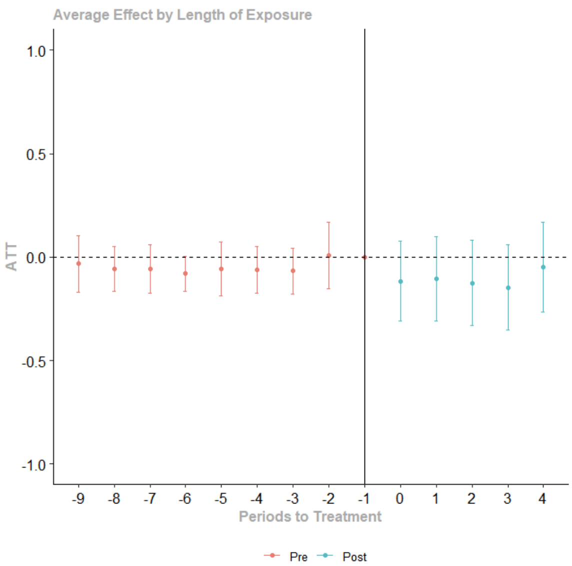
Lastly, Figure 8 presents the event study results for accidents involving automobiles, cyclists, motorcycles, and pedestrians using the alternative control group. The summary of results indicates that not only are the significance levels similar, but the size of the parameters are also practically identical to those obtained with the baseline control group. In detail, panel (a) focuses on accidents involving cyclists and shows that there is no statistically significant reduction in these accidents at the 5% level following the implementation of bike lanes. Similarly, panel (d), which examines accidents involving pedestrians, also does not show statistically significant changes at the 5% level. Conversely, panel (b) examines accidents involving automobiles and reveals statistically significant reductions in these accidents for certain periods following bike lane implementation. Panel (c) focuses on accidents involving motorcycles and also shows statistically significant reductions for some periods after the bike lanes rollout. These results reinforce the finding that bike lanes effectively reduce accidents involving motor vehicles but do not have the same significant impact on accidents involving cyclists and pedestrians.



(a) General Accidents

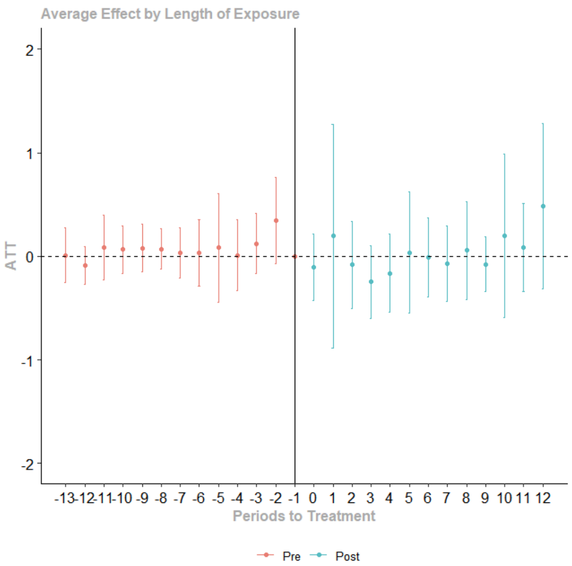


(b) Victims

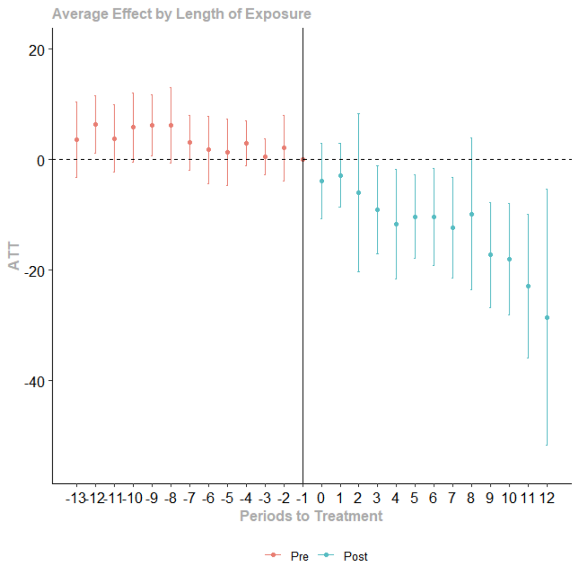


(c) Fatalities

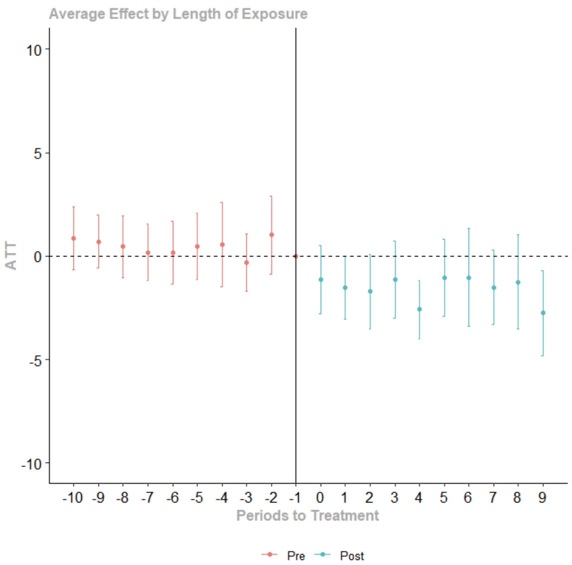
Figure 7: Event study: Effect of bike lane exposure on accidents, victims and fatalities with alternative control group



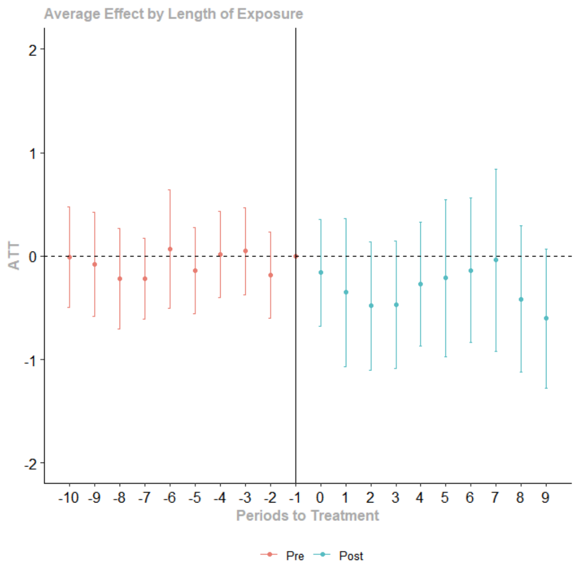
(a) Cyclist



(b) Automobile



(c) Motorcycle



(d) Pedestrian

Figure 8: Event study: Effect of bike lane exposure on different kinds of traffic-accidents with alternative control group.

6.2 Different definitions of treated units

As shown in our baseline estimates, hexagons intersected by a bike lane are considered treated, even without a precise distance cutoff. To address this limitation, we provide varying treatment extents based on the distance from hexagon centroids to the nearest bike lane network. In this specification, we define treated hexagons in two scenarios: those within 500 meters and those within 1000 meters of the nearest bike lane. This exercise allows us to verify if the results are sensitive to the definition of treated hexagon areas.

Table 3 presents the overall effects of bike lane implementation at two distances: 500m and 1000m, panel (a) and (b), respectively. For both distances, the results show a statistically significant negative impact on the number of accidents and those involving automobiles and motorcycles. At the 500m distance, the effect on total accidents is -8.864 and on automobile accidents is -15.757, both significant at the 1% level. The effect on motorcycle accidents is -1.523, also significant at the 1% level. At the 1000m distance, the effects are similar but slightly smaller: -8.302 for total accidents, -14.531 for automobile accidents, and -1.510 for motorcycle accidents. However, the effects on accidents involving victims, fatalities, cyclists, and pedestrians are not statistically significant at either distance. In summary, the magnitude of the significant estimates is very similar to those in our baseline estimates.

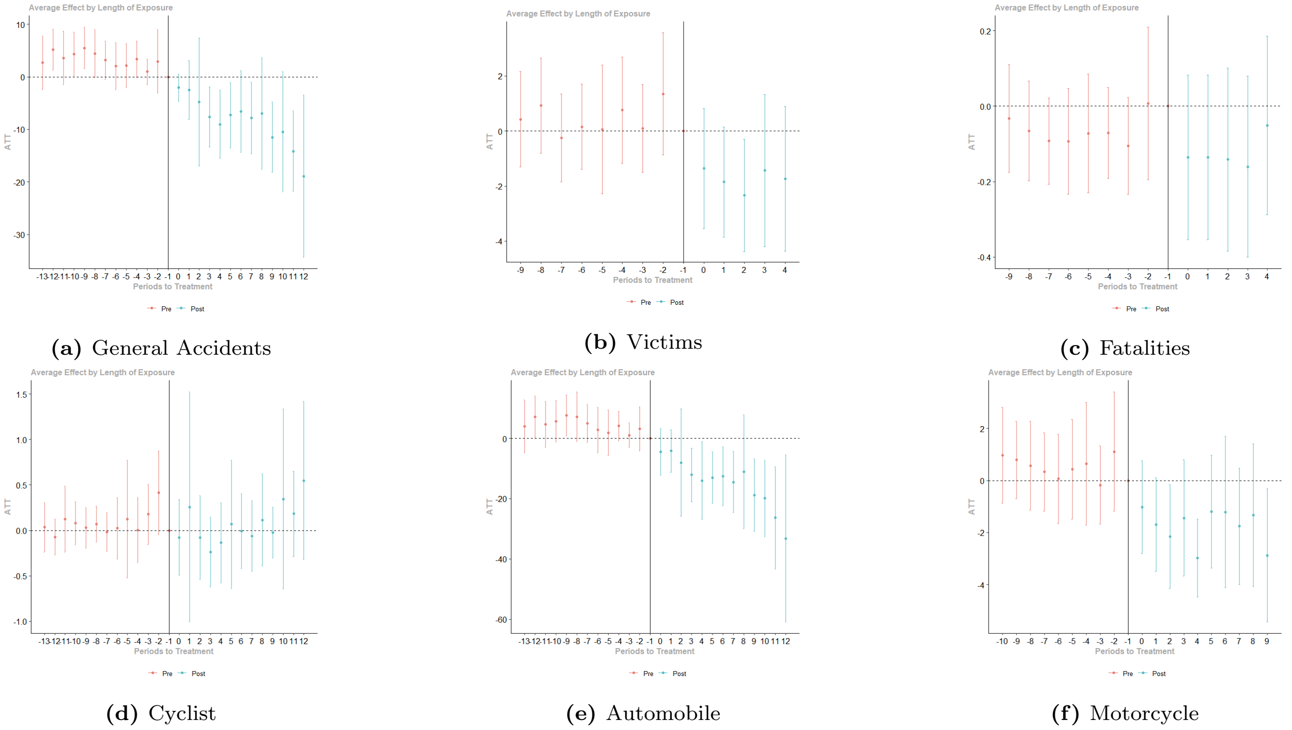
Table 3 - Varying treatment extents: Overall effects of bike lanes implementation

Panel A: 500m distance							
	Accidents (1)	Victims (2)	Fatalities (3)	Automobiles (4)	Cyclist (5)	Motorcycle (6)	Pedestrian (7)
BLI	-8.864^{***}	-0.435	-0.142	-15.757^{***}	0.087	-1.523^{***}	-0.340
	(1.743)	(0.949)	(0.085)	(3.698)	(0.158)	(0.606)	(0.254)
Hex. FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Quarter FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
No. of Hex.	418	418	418	418	418	418	418
Obs	11,224	11,224	11,224	11,224	11,224	11,224	11,224

Panel B: 1000m distance							
	Accidents (1)	Victims (2)	Fatalities (3)	Automobiles (4)	Cyclist (5)	Motorcycle (6)	Pedestrian (7)
BLI	-8.302^{***}	-0.315	-0.121	-14.531^{***}	0.082	-1.510^{***}	-0.272
	(1.461)	(0.841)	(0.074)	(3.240)	(0.146)	(0.550)	(0.222)
Hex. FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Quarter FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
No. of Hex.	645	645	645	645	645	645	645
Obs	17,470	17,470	17,470	17,470	17,470	17,470	17,470

Note: Standard errors are in parentheses and clustered at the hexagon level. *p<0.1; **p<0.05; ***p<0.01.

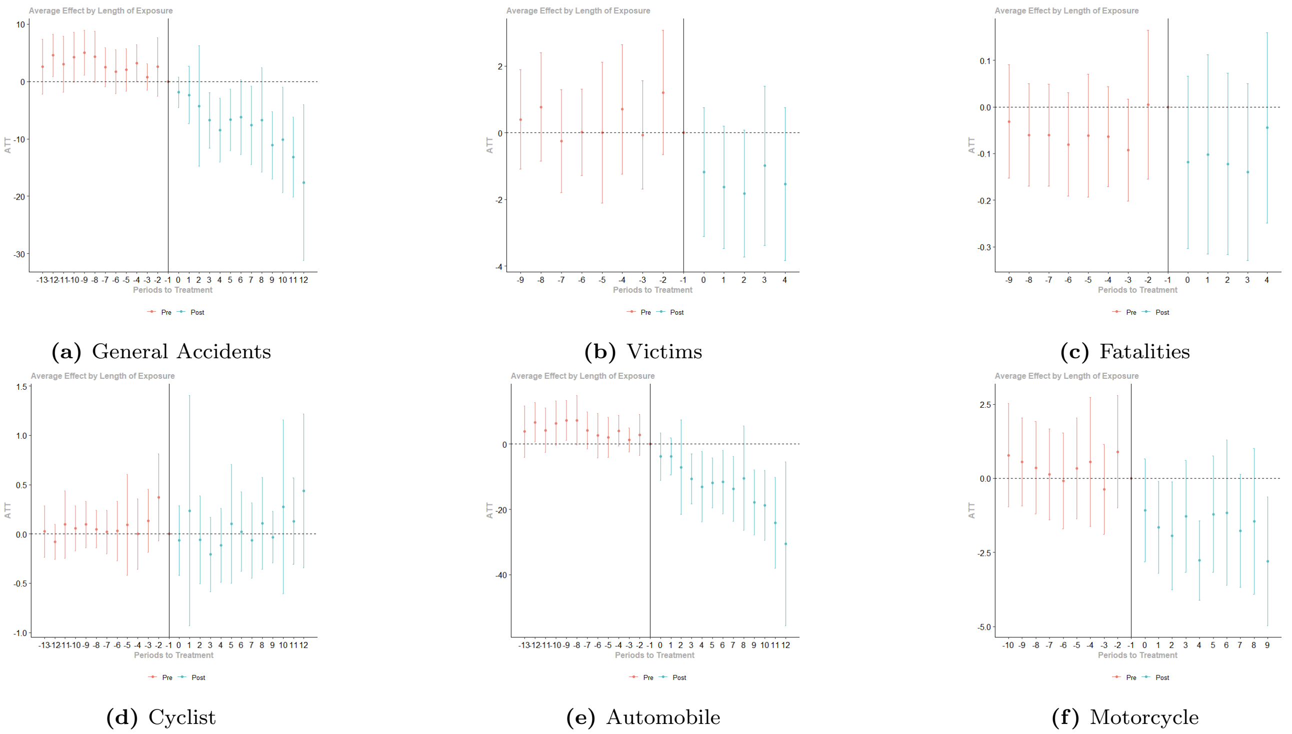
Finally, in Figure 9 and 10, we also present the event study results for varying treatment extents for 500m and 1000m, respectively. The findings are consistent with our baseline estimates.



(a) General Accidents **(b)** Victims **(c)** Fatalities

(d) Cyclist **(e)** Automobile **(f)** Motorcycle

Figure 9: Event study: Effect of bike lane exposure on different kinds of traffic-accidents. Treated Hexagons are those with centroids until 500 m of distance to the nearest bike lane.



(a) General Accidents **(b)** Victims **(c)** Fatalities

(d) Cyclist **(e)** Automobile **(f)** Motorcycle

Figure 10: Event study: Effect of bike lane exposure on different kinds of traffic-accidents. Treated Hexagons are those with centroids until 1000 m of distance to the nearest bike lane.

6.3 Additional controls

In this subsection, we present estimates that incorporate control variables. We utilize geocoded data from traffic sensors and electronic speed bumps throughout the city, which record motor vehicle flow and speed in areas with newly implemented bike lanes. This allows us to assess the impact of bike lane implementation while accounting for these covariates.

Due to data limitations from the matching process between traffic sensors and hexagon areas, we identified only ten hexagons from our baseline estimates that were within 200 meters of a traffic sensor or electronic speed bump. Consequently, we obtained average speed and motor vehicle flow information for these hexagons. Unfortunately, the small sample size prevents us from reestimating our baseline results using the Callaway and Sant'Anna (2021) approach, as this method is not suitable for small samples. Instead, we provide estimates using the Two-Way Fixed Effects (TWFE) approach, which can handle smaller sample sizes effectively.

Table 4 presents the overall effects of bike lane implementation on various types of accidents, using the TWFE approach while controlling for average speed and motor vehicle flow. In panel A, column (1) shows a significant negative impact on the number of accidents, with a coefficient of -18.252, significant at the 5% level, consistent with our baseline estimations. When additional controls are included in column (2), the negative effect becomes even more pronounced (-46.146) and remains significant at the 10% level. Similarly, in panel B, columns (7) shows a significant negative effect on accidents involving at least one automobile, with a magnitude of -29.003, significant at the 10% level. When additional controls are included in column (8), the negative effect also becomes more pronounced (-74.033) and remains significant (at the 5% level). Conversely, no statistically significant effects are found for accidents with at least one victim, fatalities, cyclists, and motorcycles.

In summary, the effects of bike lanes on the overall number of accidents and those involving at least one automobile are robust to the inclusion of additional controls for average speed and motor vehicle flow. The significant negative impact observed in the baseline estimates is confirmed even when these covariates are accounted for, suggesting that the implementation of bike lanes continues to be associated with a reduction in total accidents and automobile-related accidents. The consistency of these results across different specifications underscores the reliability of our findings.

Table 4 - Overall Effects of Bike Lanes Implementation - TWFE estimates controlling for average speed and motor vehicle flow

Panel A: Accidents and victims	Accidents		Victims		Fatalities	
	(1)	(2)	(3)	(4)	(5)	(6)
BLI	−18.252**	−46.146*	−2.040	−1.885	−-0.028	0.008
	(10.517)	(21.200)	(2.354)	(4.795)	(0.041)	(0.086)
Controls	No	Yes	No	Yes	No	Yes
Hex. FE	Yes	Yes	Yes	Yes	Yes	Yes
Quarter FE	Yes	Yes	Yes	Yes	Yes	Yes
No. of Hex.	11	10	11	10	11	10
Obs	308	163	308	163	308	163

Panel B: Different kinds of accidents	Automobiles		Cyclist		Motorcycle	
	(7)	(8)	(9)	(10)	(11)	(12)
BLI	−29.003*	−74.033**	−0.620	−0.423	0.176	−1.007
	(16.852)	(35.103)	(0.760)	(1.691)	(2.267)	(4.869)
Controls	No	Yes	No	Yes	No	Yes
Hex. FE	Yes	Yes	Yes	Yes	Yes	Yes
Quarter FE	Yes	Yes	Yes	Yes	Yes	Yes
No. of Hex.	11	10	11	10	11	10
Obs	308	163	308	163	308	163

Note: Standard errors are in parentheses and clustered at the hexagon level. *p<0.1; **p<0.05; ***p<0.01.

7 Concluding remarks

In this paper, we analyzed the effect of bike lane implementation on traffic safety performance using geocoded data aggregated by quarter on traffic accidents in the city of Recife, Brazil, between 2016 and 2022. Using the difference-in-differences estimator proposed by Callaway and Sant'Anna (2021), we provide causal evidence that the implementation of bike lanes effectively reduced multiple traffic accident outcomes, including general accidents and motor vehicles involved in crashes.

Our results indicate that the staggered rollout of bike lanes contributed to a reduction in general traffic accidents in the city, particularly those involving automobiles and motorcycles. Treated areas experienced an average of 2.5 fewer accidents per 100 crashes each quarter after the implementation of the bike lanes, with reductions of 4.5 for automobile crashes and 0.5 for motorcycle crashes. While the impact on traffic accidents may not appear substantial initially, it remains relatively significant over time. The reduction in accidents becomes more pronounced as time elapses, though its significance diminishes after the 12th quarter of exposure to the treatment. Conversely, our findings show no significant effect of the policy in reducing accidents involving victims, fatalities, cyclists, and pedestrians. These results consider fixed and time fixed effects and covariates known in the literature to influence traffic accidents. The main results are also consistent after considering different robustness checks.

The investigation may be expanded in different directions. One limitation of this paper is that there is no sufficient historical data on traffic volume for more areas in the city. We plan to deal with this point in future research, particularly considering other covariates that are correlated with traffic volume. We also intend to present other robustness checks by using a machine learning approach to detect potential future treated areas and use them as counterfactual.

From a policy perspective, this study provides evidence that the implementation of bike lanes can effectively reduce traffic accidents. Our findings suggest that safety benefits following the bike lane rollout increase over time and not only immediately after its implementation. Becoming more pronounced as the infrastructure is used. This gradual improvement underscores the importance of incorporating safety-based incentives in urban planning and infrastructure projects to reduce traffic accident outcomes.

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