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Speed Limits in São Paulo and the Actions for Road Safety and Air Quality

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Abstract: Studies carried out have revealed that every day around three thousand and twelve people lose their lives in the world due to traffic accidents and poor air quality. Large cities, with their millions of inhabitants and vehicles, face many problems relating to vehicular traffic. In 2015 the speed limit was modified on several roads in the city of São Paulo-Brazil. However, in 2017 the speed limits were increased again, but not on all previous routes. This study analyzed the impact of this change on the number of accidents and pollutant concentrations, over a period of ten years, comparing the periods before and after the implementation of the measure, using real data collected and provided by the authorities of the city and the state transit and environmental companies, on more than forty routes and two nearby air quality stations. The results show a clear reduction in the number of accidents without victims on the roads of the city of São Paulo starting in 2010. However, the restrictive measures imposed by government officials may have contributed to the decrease in the number of accidents, but the number of fatalities has not changed much. Air pollution has not improved substantially with speed changes, as new speed increases have been linked to new episodes of congestion. The average number of fatalities due to accidents has been increasing since 2010 and accidents are becoming more serious. The application of a general linear statistical model (GLM) estimated the impact of the speed reduction policy in terms of the number of injuries avoided per month: 43.4 and 14.1 on other roads and on Pinheiros marginal, respectively. The results highlight the need for a constant data collection by the authorities in cities with high vehicle traffic. The important temporal time trend in terms of reduction of injuries but not in terms of fatalities and air quality, shows the need to apply joint public policies, not only speed reduction, but also the use of new technologies and raising drivers' awareness of the problem.

Keywords: traffic accidents; speed limit; air quality; São Paulo

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1. Introduction

Transport systems move people and goods, contribute to the development of national economies and facilitate access to employment and services, improving overall the society's quality of life. However, the traffic of vehicles at high speeds has major adverse impacts in terms of road accidents with consequent deaths and injuries, as well as material, economic and environmental impacts, such as noise and pollutant emissions [1]. Major risk factors that trigger accidents were identified [2]: lack of use of seat belts and child restraint systems, non-use of helmets, driving under the influence of alcohol and drugs, lack of adequate infrastructure and inadequate or excessive speed [3]. Based on the recommendations of the World Report on road traffic injuries and the Commission for Global Road Safety, it was recommended that new road projects should be as tolerant as practicable to reduce the consequences of driver errors and failures.

In the period between 2011 and 2020, the World Health Organization (WHO) proclaimed the "First Decade of Action for Road Safety", for the purpose of stabilizing and reducing the forecast level of road traffic fatalities around the world by increasing activities conducted at the national, regional

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and global levels [3]. Regarding the period between 2021 and 2030, WHO proclaimed the "Second Decade of Action for Road Safety" to reduce the number of traffic accidents by half [4].

It may be observed that the number of traffic accidents remains unacceptably high worldwide: more than 1.35 million people being killed and up to 50 million injured per year. Developing countries concentrate 90% of all the victims, being the leading cause of death worldwide for children and young people between 15 and 29 years of age [4]. Air quality traffic related deaths also increased worldwide. Air pollution is among the five biggest causes that contribute to global mortality, accounting for around 4 million deaths per year [5]. Cities with accelerated urban surface growth are deeply impacted by air pollution, leading to a scenario of environmental degradation and unsustainable standards [6].

An important question for the authorities is whether speed limits should be lowered to bring good results to society and associated cost-benefits. Although the lowering of speed limits implies increases in transportation costs and travel time, also reduces pollution rates, fuel consumption and accidents [7]. Hosseinlou et al. [8] used a mathematical model to determine the optimal speed for the vehicles depending on location, socio-economic and technological factors. Aarts and Van Schagen [9] reviewed empirical studies and concluded that the crash rate increases with speed increases: vehicles that move much faster than the surrounding traffic have an increasing crash rate. Kroyer et al. [10] developed a risk curve in urban environments observing that increases in vehicle speed have significant impacts on fatal accident risks (cautions need to be taken when considering the increase in speed and other parameters). Automotive safety systems designed to avoid accidents and road safety are also important [11]. In this sense, Doecke et al. [12] studied the relationship between speed limits and injury severities for different crash types and results have demonstrated a generally positive exponential relationship between speed limits and fatality rates. Highways permitting motorists to drive more than 100 km/h are only safe from fatal accidents if they have excellent conditions of use, good geometrical project, and safe roadside design. These studies found that for fatality rate threshold of 1 in 100 crashes, the safe speed limits are: 40 km/h for pedestrian crashes, 50 km/h for head-on crashes, 60 km/h for hit fixed object crashes, 80 km/h for right angle, right turn, and left road/rollover crashes and 110 km/h or more for rear-end crashes. Drivers' attitudes and behaviors can also influence the occurrence of accidents [13].

WHO stresses the importance of the local authorities to legislate on speed limit reduction [14] at schools and commercial areas, representing traffic generator hubs attracting large vehicle and pedestrian flows. The city of São Paulo, in compliance with the United Nations (UN) recommendations, started a life protection program in 2013, with the objective of reducing death rates from traffic accidents to a maximum of three deaths for every 100,000 inhabitants in by 2030 [3]. A study carried out in the city of São Paulo concluded that the speed reduction programs applied since 2015 had reduced both the average speed of motor vehicles and mortality resulting from traffic accidents, the latter being more pronounced among people over 50 years old [15,16]. In addition to reducing the number of accidents, lowering the speed limit can also help reduce polluting emissions, fuel consumption and travel time [8]. In studies carried out in Spain, the authors demonstrated that the percentages of reduction of these factors vary according to the characteristics of each locality [7].

The vehicle fleet in the Metropolitan Region of São Paulo consists of more than 7 million vehicles, including heavy vehicles such as trucks, buses, minibuses, pickup trucks and vans [17]. In 2015, the speed limit was modified on several roads in the city of São Paulo, including those on the Tietê and Pinheiros highways [18]. These highways represent two of the most important roads in the city, which interconnect the main highways, have a large flow of vehicles (with a consequent large emission of pollutants) and concentrate ~4.1% of fatal traffic accidents (occupying the first two positions of this type of accidents within the area under the responsibility of the municipality). In January 2017, speed limits on the two marginals returned to their highest values in 2015, although they remained at more restrictive levels on other roads in the city [19]. A study in São Paulo showed that this speed reduction policy adopted in 2015 led, in its first 18 months of operation, to a 21.7% reduction in the number of accidents, including those with and without fatalities [20]. A similar reduction percentage was previously achieved in the region of Catalonia (Spain), where road speeds were reduced from 120 km/h and 100 km/h to 80 km/h in July 2007. As was the case of São Paulo, the newly elected government revoked this measure in February 2011, allowing a return to previous speed limits and masking impacts of the policy [21].

Our objective in this paper is to analyze whether the reduction in the speed limit on marginal roads in São Paulo contributed to the decrease in the occurrence of traffic accidents, and whether the reduction on other roads in the city, still in force, also had an influence. The study period is between 2010 and 2020, covers the period of the United Nations "Decade of Action for Traffic Safety" and uses a 10-year database from São Paulo to assess the impacts of speed reduction and increase policies on traffic safety: frequency of accidents, fatalities, and injuries. Finally, improvements in air quality due to speed reduction strategies are tested in the Pinheiros highway (considered as a case study).

2. Materials and Methods

The Tietê marginal has an extension of ~ 23 kilometers, interconnecting the Ayrton Senna and Pinheiros highways, having three classes of lanes, with a road classification composed of fast rapid transit (FT), central lanes (C) and arterial lanes (A). The Pinheiros marginal also has an extension of ~ 23 kilometers, interconnecting the Tietê marginal and important avenues. This highway has two classes of lanes, with a road classification composed of fast rapid transit and arterial lanes. In the two marginals, speeds have been reduced from 07/20/2015 to 01/24/2017 and increased again since 01/25/2017. Table 1 shows the dates and speed limits adopted in each period for the two highways and for light and heavy-duty vehicles (LDVs and HDVs). Figure 1 shows the layout of the two marginals and their surroundings. The Tietê and Pinheiros marginals have 51 and 26 locations, respectively, with radar surveillances installed in their corresponding segments [18]. Supplementary material provides information about the other roads.

In addition, forty other roads in the area under the responsibility of the municipality were studied. These forty local roads have a total length of ~ 246 km: 19 roads with radar and speed bumps (47.5%), 15 roads with only radar (37.5%) and 6 roads with only speed bumps (15%). In the forty other local roads, speeds have been reduced to 50 km/h in July 2015 and continued at their reduced level.

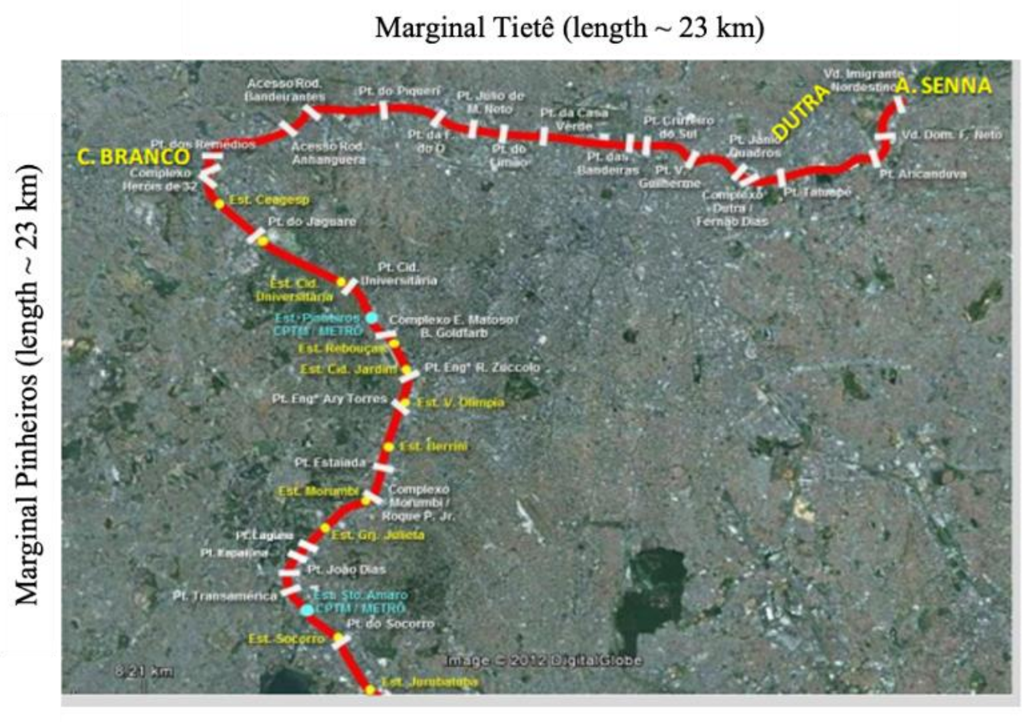

Figure 1. Layout of the Tietê and Pinheiros highways: location of bridges/viaducts/ramps (in white), train stations (in yellow and blue) and main road connections (Dutra, C. Branco and A. Senna highways). Source: adapted from [19].

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Table 1. Dates and speed limits adopted in each period for the Tietê and Pinheiros highways and for the vehicle types (heavy and light duty).

Lane types	Light duty vehicles	Heavy duty vehicles	Light duty vehicles	Heavy duty vehicles	Light duty vehicles	Heavy duty vehicles
	Until 07/19/2015		From 07/20/2015 to 01/24/2017		Since 01/25/2017	
FT[1]	90 km/h	70 km/h	70 km/h	60 km/h	90 km/h	60 km/h
C[2]	70 km/h	70 km/h	60 km/h	60 km/h	70 km/h	60 km/h
A[3]	70 km/h	70 km/h	50 km/h	50 km/h	60 km/h	60-50 km/h

[1] fast traffic lanes, [2] central lanes and [3] arterial service lanes.

3.1. Accident Modelling

Data on traffic accidents from 2010-2020, including dead and injured, were provided by the São Paulo Traffic Engineering Company (CET) through reports and other requests for information [22]. A General Linear Model (GLM) was fitted to the monthly data on traffic accidents and victims (death and injured), using as independent variables (fixed factors): location, year, month and speed reduction/increase policies (speed scenarios). In the accident model, the combinations of year and month of implementation/removal of the transport policy within each year were used as random factors. There were months in the city in which the number of accidents decreased significantly due to the decrease in speed, especially starting from the year 2015. The regression model estimated the accidents in month *t*, during the period 2011-2020, using the number of dead and injured on the marginal roads Pinheiros and Tietê and the other forty roads:

$$\text{Accidents (dead or injured monthly } i\text{, location } j\text{, month } t)_{i,j,t} = a_0 + a_1 P_t + W_t a_2^w, \quad (1)$$

where P_t is a dummy variable ranging from 1 to 0 (1 for months with implementation of a speed reduction policy and 0 for months without such a reduction), reflecting month *t* related to traffic speed restrictions; a_0 (intercept) and a_1 (slowdown scenario effect) are regression coefficients obtained by ordinary least squares. Time trends at location *j* were included to control for the effects of transport policies in the data period. Therefore, W_t is a vector of annual records that can impact *i* accidents because of the implementation of the measures and a_2^w are the regression coefficients related to the years 2011 to 2020.

3.2. Interactions between Traffic Parameters, Accidents and Air Quality

In January 2017, a technical note appeared advocating for speed variations based on studies of traffic flows (and their respective braking distances for light and heavy vehicles) and levels of service that take into consideration ranges of vehicle density per traffic lane [23]. The level of service is a qualitative assessment of the road traffic operating conditions. The level of service considers speed, travel time, traffic restrictions or interruptions, degree of freedom of maneuver and comfort. Finally, the level of service classifies road segments based on their speed and corresponding traffic volumes [24]. Additionally, this technical note recommended some measures that should be implemented especially on marginal roads along with speed increments. The main recommended measures were the improvement of speed regulation signage, educational and warning signage (such as prohibition of mobile phone use while driving, implementation of pedestrian crossings at junctions, use variable electronic message boards, increased inspection of motorcycles, expansion of traffic operational equipment on these roads and inhibition of the presence of street vendors). Along with these measures, pavement conditions can also have a strong impact on the number of accidents [25].

The relationships between main traffic parameters, flow *F* (number of vehicles/h/lane), mean speed *s* (in km/h) and density *D* (vehicles/km/lane), are defined according to the following equation:

$$F = s\,D, \quad (2)$$

The capacity *C* of a road is the maximum value of the vehicle flow that can circulate through a section with uniform characteristics. This maximum value corresponds to the critical density. Transport policy measures that avoid exceeding the capacity of roads are preferred to reduce accidents and pollution simultaneously [7,21].

3. Results and Discussion

3.1. Accident Trends

Figure 2 shows the rate of traffic fatalities per 100,000 inhabitants in São Paulo, with the goal of reducing accidents by half between 2010 and 2020, from 12 to 6. It can be observed that until 2017 there was a considerable reduction to 6.6, almost reaching the target of the United Nations and indicating the effectiveness of the road safety interventions implemented during this period [4]; however, from 2017 onwards this rate fluctuated, showing the need to continue efforts to reduce accidents [18].

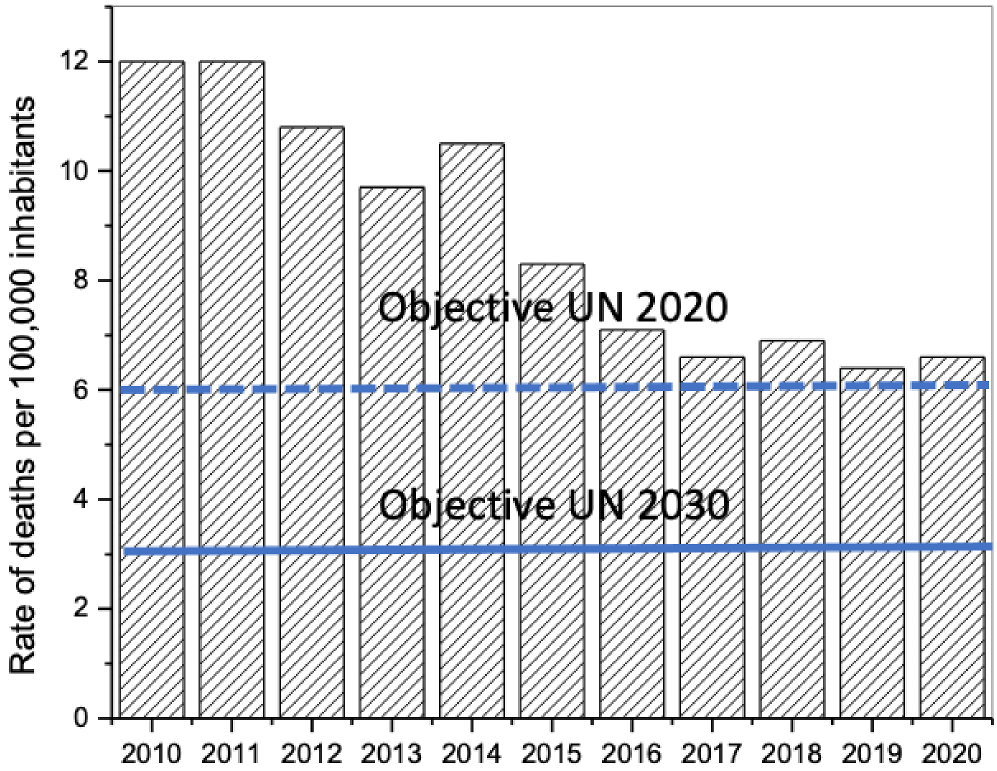

Figure 2. Numbers of deaths per capita from traffic accidents in the City of São Paulo. Source: adapted from [18].

The analyses presented in Figure 3 separated the data from the Pinheiros and Tietê marginal roads from the other forty roads – between 1st January (2010) and 31st December (2020) of the UN decade of safe actions on road traffic – to identify possible similarities between these pathways. As a result of the reduction of speed limits on several roads in the city in 2015, the number of accidents with injuries and fatalities showed a downward trend, with significative differences between the marginal roads and the other roads. The data in Figure 3 indicate a strong downward trend in the number of injuries on both the marginals roads and the other roads. This downward trend is not clearly observed regarding fatalities, especially on the Pinheiros highway. For the other forty roads, comparing the periods between 2010 and 2014 and between 2015 and 2020, the total number of accidents, with and without victims, dropped by 53% (Table 2).

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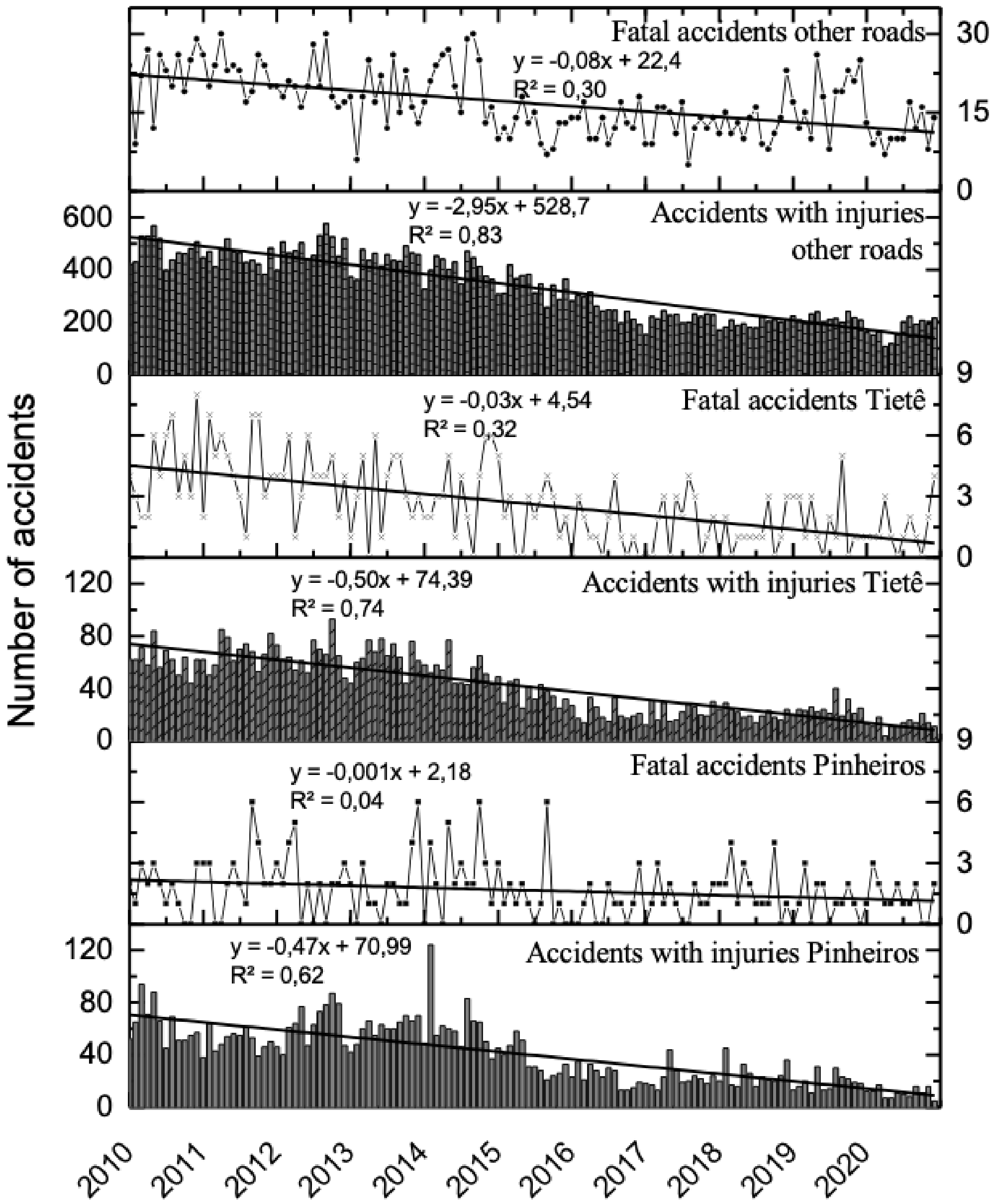

Figure 3. Trend in the period of the monthly number of fatalities and injuries on marginal highways and forty other roads between 2010 and 2020.

Table 2. Descriptive statistics of accidents with fatalities and injuries on marginal roads and other roads per year.

Year	Mean fatalities (±sd)¹	Sum of fatalities²	Difference in fatalities (%)³	Mean injuries (±sd)¹	Sum of injuries²	Difference in injuries (%)³
Pinheiros marginal						
2010	0.03±0.18	20	_	1.22±0.56	764	_
2011	0.06±0.28	28	40.00	1.21±0.58	607	-20.55
2012	0.04±0.20	25	-10.71	1.21±0.58	762	25.54
2013	0.04±0.19	23	-8.00	1.18±0.50	725	-4.86
2014	0.05±0.23	30	30.43	1.21±1.80	755	4.13
2015	0.05±0.23	18	-40.00	1.15±0.56	435	-42.38
2016	0.04±0.20	11	-38.89	1.11±0.45	281	-35.40
2017	0.06±0.24	14	27.27	1.19±0.63	270	-3.91

2018	0.09±0.33	22	57.14	1.21±1.08	297	10.00
2019	0.06±0.24	13	-40.91	1.12±0.62	230	-22.56
2020	0.13±0.34	16	23.08	1.09±0.67	132	-42.61
Total		220			5,258	
Tiete marginal						
2010	0.08±0.30	53	_	1.19±0.69	744	_
2011	0.08±0.29	54	1.89	1.25±0.92	808	8.60
2012	0.07±0.27	47	-12.96	1.19±0.71	785	-2.85
2013	0.06±0.26	38	-19.15	1.18±0.64	774	-1.40
2014	0.07±0.26	38	0.00	1.16±0.64	645	-16.67
2015	0.07±0.29	28	-26.32	1.15±0.60	441	-31.63
2016	0.07±0.27	15	-46.43	1.19±0.72	259	-41.27
2017	0.09±0.32	20	33.33	1.12±0.87	264	1.93
2018	0.06±0.24	14	-30.00	1.12±0.54	250	-5.30
2019	0.08±0.28	21	50.00	1.17±0.68	297	18.80
2020	0.12±0.32	17	-19.05	1.07±0.68	158	-46.80
Total		345			5,425	
Other forty roads						
2010	0.06±0.26	262	_	1.30±0.93	5750	_
2011	0.06±0.27	276	5.34	1.26±0.85	5415	-5.83
2012	0.05±0.24	244	-11.59	1.26±0.83	5846	7.96
2013	0.05±0.22	211	-13.52	1.21±0.70	5270	-9.85
2014	0.06±0.27	263	24.64	1.20±0.83	4870	-7.59
2015	0.04±0.20	142	-46.00	1.19±0.67	4070	-16.43
2016	0.06±0.25	160	12.68	1.17±0.67	3035	-25.43
2017	0.07±0.27	150	-6.25	1.20±0.70	2598	-14.40
2018	0.08±0.28	155	3.33	1.17±0.65	2348	-9.62
2019	0.09±0.32	213	37.41	1.14±0.68	2595	10.52
2020	0.08±0.29	137	-64.32	1.22±0.73	2088	-19.54
Total		**2,213**			**43,885**	

[1] mean and standard deviation (sd) per day, [2] total sum per year and [3] percentage differences between consecutive years for the total number of fatalities and injuries.

In a study carried out in Sweden, the authors showed that reducing speed from 50 to 40 km/h reduced the number of accidents with serious injuries by 11% after 1 year, on similar roads to the marginals in São Paulo, with no parking lots and sidewalks [26]. But as the authors themselves report, there is a complex and non-consensual relationship in the study between the decrease in the speed limit and the number of accidents [27]. In the US, there is a similar national trend in road safety [11]. Many factors may contribute to the trend in this study, such as the improvement of vehicle safety technologies. Therefore, there is a strong underlying trend in the data and linear models can provide a basic understanding of the evolution of traffic safety. However, using simply linear models we cannot capture all the impacts of speed changes, as shown by the relative stable number of accidents and injuries over the last five years in Figure 3. Other methods, such as time series modeling, can capture the complex dynamics and underlying trends in road safety data, particularly when assessing the impact of speed changes and other policy interventions over time [27].

Table 2 shows the annual data for accidents with and without victims in the three locations studied. The number of accidents with and without victims decreased in 2015 but fluctuated in subsequent years. In 2019, increased on the Tietê marginal and other roads, causing an increase in the number of deaths due to accidents. In general, the number of injures and deaths due to traffic accidents show a contradictory situation. Although the accidents with victims have decreased, they have been increasingly serious and the number of deaths due to accidents has increased mainly since 2016 on all roads.

Between 2010 and 2020, the 9,032 accidents on the marginal roads represent 20% of the total of 44,958 accidents studied in this work (other forty roads, with 35,926 accidents, represent 80%). Regarding accidents with fatalities, the Tietê marginal registered higher records in the period than the Pinheiros marginal, except in 2018. The outbreak of the COVID-19 pandemic in 2020 motivated containment measures taken to prevent the spread of the virus, that can have an impact on traffic dynamics in the city of São Paulo. Although the restrictive measures imposed by government officials may have contributed to the decrease in the total number of accidents on main roads, such as the two marginal roads, the number of fatalities has not changed significantly. During this atypical year, speed variations in the same or between different lanes of the highway may have increased the chances of accidents with serious or fatal victims [28].

The percentage difference between consecutive years in Table 2, both for the total number of fatalities and injuries, highlighted that there was a reduction of 40% and 26% in fatal accidents in 2015, when there was a reduction in the speed on the Pinheiros and Tietê marginals, respectively (42% and 32% related the injuries). In the other roads for the same year there was a reduction of 46% (fatalities) and 16% (injuries). In January 2017 there was an increase in the speed of marginals, related to an increase of 27% (fatalities) and a reduction of 4% (injuries), and an increase of 33% (fatalities) and 12% (injuries), in the Pinheiros and Tietê marginals respectively. In the other roads, both fatal accidents (6%) and accidents with injuries (14%) were reduced. This indicates that the speed reduction measure was efficient and if it had been kept within the marginals, deaths and accidents would probably have been avoided. Most of the other forty roads had decreased their speed since 2015, showing a considerable reduction in the number of accidents; the number of fatalities was similar in the subsequent three years period (2016 to 2018). However, recorded accidents with injuries showed a significant decrease in the period from 2015 to 2018. A study in Norway evaluated the before and after of a speed reduction scenario (from 80 to 60 km/h), which extended for 5 months. The results showed a 25-35% reduction in accidents with injuries, but the authors concluded that the decrease in accidents may not be the only cause of the speed reduction [29].

3.2. Accident Modelling

Application of a general linear statistical model (GLM) shows the impact of speed reduction policies and temporal trends on the monthly number of injuries and deaths (Table 3). The regression coefficients related to transport policies and temporal trends were statistically significant for the number of injuries and there was a reduction on the marginals and the other roads in the region. The effects of transportation policies have little impact on reducing the timing of fatalities. The regression coefficients of the models in São Paulo confirm the linear trends shown in Figure 3 and the descriptive statistics in Table 2. During the period in which speed limits were reduced, the effects of transportation policies in relation with the temporal reduction in the number of injuries are different depending on the roads studied: 14.1 fewer injuries per month for Pinheiros marginal, 5.7 for Tietê marginal and 43 .4 for the other routes (95% confidence intervals and standard errors were estimated). The decreasing values of the regression coefficients over the years of the survey show the growing importance of law enforcement measures. For example, in 2010 the values of the number of monthly injuries (52.7, 48.8 and 261.8) were higher than in the 2020 reference year for Pinheiros marginal, Tietê marginal and other roads, respectively.

Table 3. Effects of speed reduction policies and temporal trends on road safety in São Paulo; forecast of injury and death rates during the months of the 2010-2020 period; data for the Pinheiros and Tietê marginals and other roads[1].

Var (Uni.)	Injuries (#/month)	Fatalities (#/month)	Var (Uni.)	Injuries (#/month)	Fatalities (#/month)	Var (Uni.)	Injuries (#/month)	Fatalities (#/month)
Pinheiros marginal			Tietê marginal			Other roads		

Speed reduction policy [2]			Speed reduction policy [2]			Speed reduction policy [2]		
	-14.1±5.7*	-0.5±0.7		-5.7±4.4	-0.1±0.8		-43.4±22.7*	-2.5±2.8
Time trend			Time trend			Time trend		
2010	52.7±4.6*	0.3±0.6	2010	48.8±3.6*	3.0±0.6*	2010	261.8±27.0*	7.9±3.3*
2011	39.6±4.6*	1.0±0.6	2011	54.2±3.6*	3.1±0.6*	2011	233.9±27.0*	9.1±3.3*
2012	52.5±4.6*	0.7±0.6	2012	52.2±3.6*	2.5±0.6*	2012	269.8±27.0*	6.4±3.3
2013	49.4±4.6*	0.6±0.6	2013	51.3±3.6*	1.7±0.6*	2013	221.8±27.0*	3.6±3.3
2014	51.9±4.6*	1.2±0.6*	2014	40.6±3.6*	1.8±0.6*	2014	188.5±27.0*	8.0±3.3*
2015	32.3±5.4*	0.4±0.7	2015	25.9±4.0*	0.9±0.7	2015	136.3±21.1*	-1.3±2.6
2016	26.5±7.3*	0.1±0.9	2016	14.1±5.7*	-0.1±1.0	2016	78.9±14.7*	1.9±1.8
2017	12.7±4.6*	-0.1±0.6	2017	9.3±3.6*	0.3±0.7	2017	42.5±14.7*	1.1±1.8
2018	13.7±4.6*	0.5±0.6	2018	7.7±3.6*	-0.2±0.6	2018	21.7±14.7	1.5±1.8
2019	8.2±4.6	-0.3±0.6	2019	11.6±3.6*	0.3±0.6	2019	42.2±14.7*	6.3±1.8*
2020	-	-	2020	-	-	2020	-	-
Regression [3]			Regression [3]			Regression [3]		
R^2	0.79	-	R^2	0.84	-	R^2	0.92	-
Mean	34.8	1.5	Mean	39.0	2.6	Mean	331.8	16.7

[1] the table shows the coefficients and standard errors of the regressions for the Pinheiros and Tietê roadways and other roads in the city of São Paulo; a total of 132 observations were considered for each type of road and the research period was from January 2010 to December 2020 (11 years), including monthly averages (Table 2); [2] speed changes were treated as "dummy" variables: speed reductions in the marginals from July 2015 to January 2017 and reductions in "other lanes" from the beginning of September 2015 to the present; *analysis of variance $p < 0.01$; [3] regression model fitted by least squares. Average: dependent variable (number of monthly injuries and deaths, 2010-2020).

The reduction of injuries was also possible by radar surveillance systems in all lanes, even with the continued increases in vehicle flows. The importance of transport policies is reflected by the values of the multiple regression coefficients of GLM (R^2). These coefficients improved compared to the coefficients of the simple linear model of Figure 2, especially in the case of Pinheiros marginal (27%), going from 0.62 to 0.79. A significant reduction in the number of deaths per month was also observed in some years in the case of Tietê marginal (2010-2014) and other roads (2010-2011, 2014 and 2020). The fact of the implementation of an uneven speed reduction policy in the city – the speed on marginal roads experienced a reduction from July 2015 to January 2017 and on the other roads the speed reduction came into force from the beginning of September 2015 to the present time – can explain the difference in the number of injuries between the marginals and the other roads. If the speed had not been increased again in the two marginals from February 2017, the reduction in the number of deaths could have been even greater. Keeping the other factors constant, the reduction in speed on the other roads in São Paulo was related to the decrease in fatalities of 2.5 deaths per month (-0.5 and -0.1 deaths per month on Pinherios and Tietê marginal roads, respectively). In Table 3, speed reduction policy was treated as a single dummy variable.

Other effects could have been tested in the model. For example, climatic conditions were not considered in this study. In this sense, Naik et al. [30] showed that rain and warmer air temperatures can lead to more serious accidents. Another study carried out in Croatia showed that fatal accidents occur more frequently on urban links, at night, with poor visibility, speeding and male drivers [31]. Therefore, fluctuations in traffic volume may also have led to changes in accidents, deaths and injuries. In the municipality of São Paulo, the traffic volume from 2010 to 2019 increased by 15% from

6.3 to 7.3 million vehicles per day [32]. Taking all these changes into account, realistic predictions of accidents, injuries and deaths can be made with greater accuracy. By adding other factors and variables, the assumption between accidents and time (month or year) could not be linear, like the regression models applied in this study (Table 3). Instead of linear models, by incorporating exposure measures and developing time series models, researchers can gain deeper insights into the dynamics of accident or fatality rates over time, identify causal factors, evaluate the impact of interventions and make informed predictions for future road safety outcomes [30]. Future research in São Paulo plans to develop this type of non-linear models over time.

3.3. Pinheiros Marginal Case Study

Collaborating with experts in statistics, transportation engineering, and data science can further enhance the modeling process and its interpretation in road safety studies [27]. Impact factors (speed, vehicle flows, exposure to pollutants and other road such as congestion episodes) can be quantified in terms of traffic parameters and relationships on some of the highway segments sampled in this study (Equation 2). In this sense, Figures 4 and 5 show statistical traffic models on the Pinheiros highway, based on hourly relationships of pairwise traffic parameter, which can be rigorously compared with the corresponding accident data (detailed accidents, deaths and injuries per year and month at aggregate levels). In the analyzed section of the Pinheiros highway, Eusébio Matoso bridge (direction Castelo Branco), we can observe that congestion episodes increased during the speed increase scenario (period from 25/01/2017 to 31/12/2018, Figure 5), compared to the speed reduction scenario (period from 29/05/2015 to 24/01/2017, Figure 4). More episodes of congestion in this section during the period of increased speed, years 2017 and 2018, were related to the increase in the number of deaths between 27-57% (Table 2 and Figure 3), contrary to what was expected initially by the São Paulo City Council.

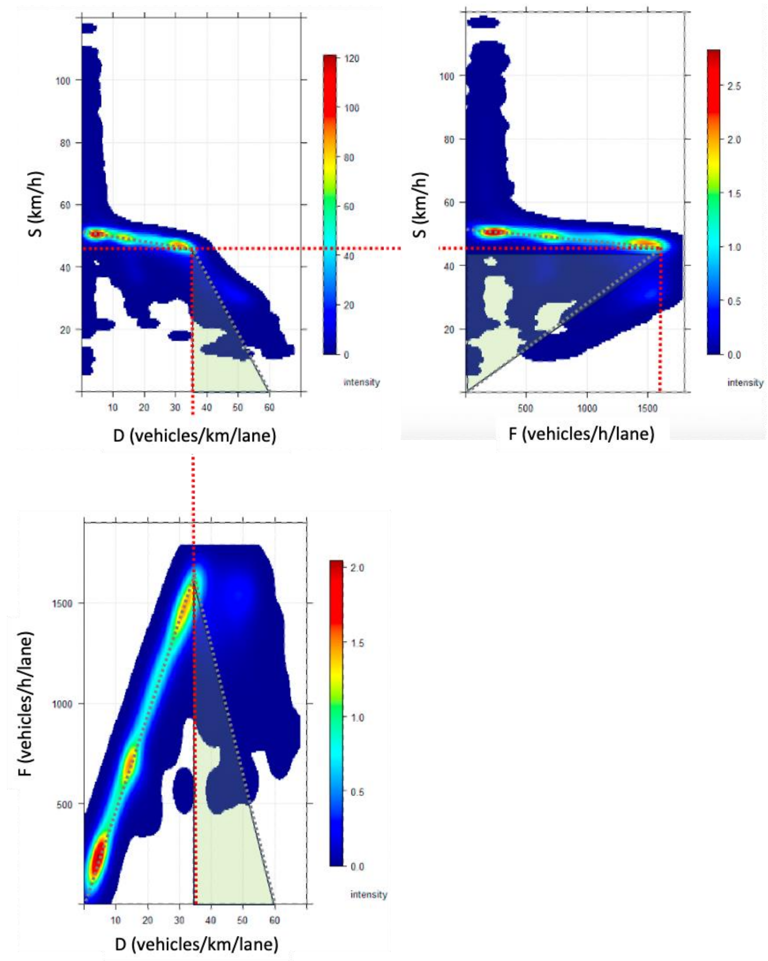

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Figure 4. Relationships of *S*-speed (in km/h), *D*-density (in # vehicles/km/lane) and uninterrupted *F*-flow of vehicles (in # vehicles/h/lane) in the Pinheiros marginal, measured by a permanent radar located next to the station CETESB in the direction Castelo Branco, in a speed reduction scenario from 29/05/2015 to 24/01/2017. Notes: colors represent the frequency of speed/density/flow combinations (heat map); free flow speed (70 km/h, maximum speed, red bars), maximum density (total lockdown at 60 veh/km/lane) and maximum capacity (~ 1600 veh/h/lane, ~ 35 veh/km/lane and ~ 45km/h) are determined by the three parameters of the traffic fundamental Equation 2; green triangle areas underlined graph regions with forced traffic.

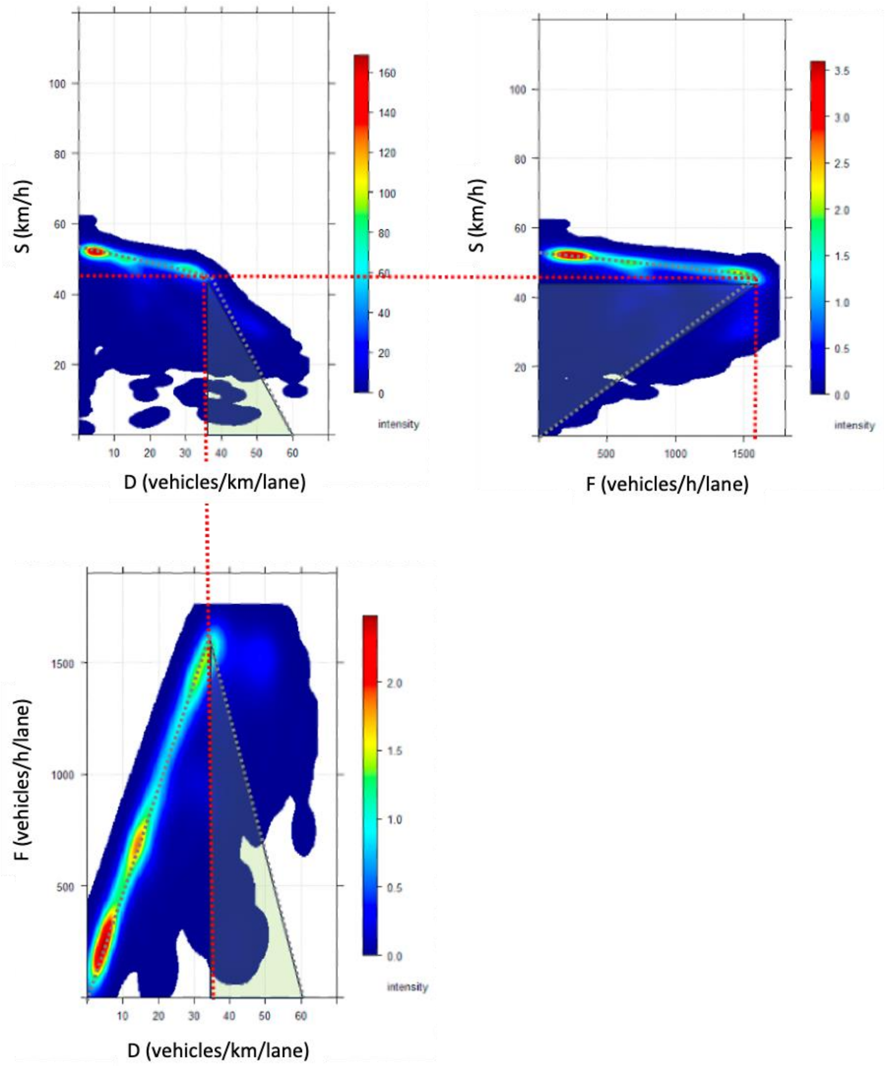

Figure 5. Relationships of *S*-speed (in km/h), *D*-density (in # vehicles/km/lane) and uninterrupted *F*-flow of vehicles (in # vehicles/h/lane) in the Pinheiros marginal, measured by a permanent radar located next to the station CETESB in the direction Castelo Branco, in a speed increase scenario from 25/01/2017 to 31/12/2018. Notes: colors represent the frequency of speed/density/flow combinations (heat map); free flow speed (90 km/h, maximum speed, red bars), maximum density (total lockdown at 60 veh/km/lane) and maximum capacity (~ 1600 veh/h/lane, ~ 35 veh/km/lane and ~ 45km/h) are determined by the three parameters of the traffic fundamental Equation 2; green triangle areas underlined graph regions with forced traffic.

The worsening of traffic accidents was associated with exposure to pollutant concentrations. Analyzing the air quality data from the CETESB station located in Pinheiros, next to the traffic segment analyzed on the Eusébio Matoso bridge, we can see that the improvement of NO_2 and CO concentration trends stopped (Figure 6a,b) due to the increase in traffic. For example, in the segment located on the Pinheiros highway, Eusébio Matoso bridge (direction Interlagos, IT), the average

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number of cars during working days increased from 6000-6250 vehicles per hour per direction to 6500-6750 (from 2016 to 2017). In this section, car flows exceeded 8000 vehicles per hour in each direction during peak-hours (7 a.m. to 10 a.m. and 5 p.m. to 8 p.m.). In this section, increases in vehicle flow and related congestion episodes increased the relationship between the hourly concentration of pollutants (NO_x in µg/m³ and CO in ppm) and traffic (in number of light duty vehicle units per hour per direction). Figures 6c-6d and 6e-6f show the air concentration and car flow relationships, during the central period of working days (7 a.m.-8 p.m.), for NO_x and CO and for the speed reduction and increase scenarios, respectively. Due to higher air concentrations and vehicle flows in the speed increase scenario, the slope of the regression lines increased (Figure 6e,f), compared to the speed reduction scenario (Figure 6c,d), showing worsening local air quality conditions due to traffic management.

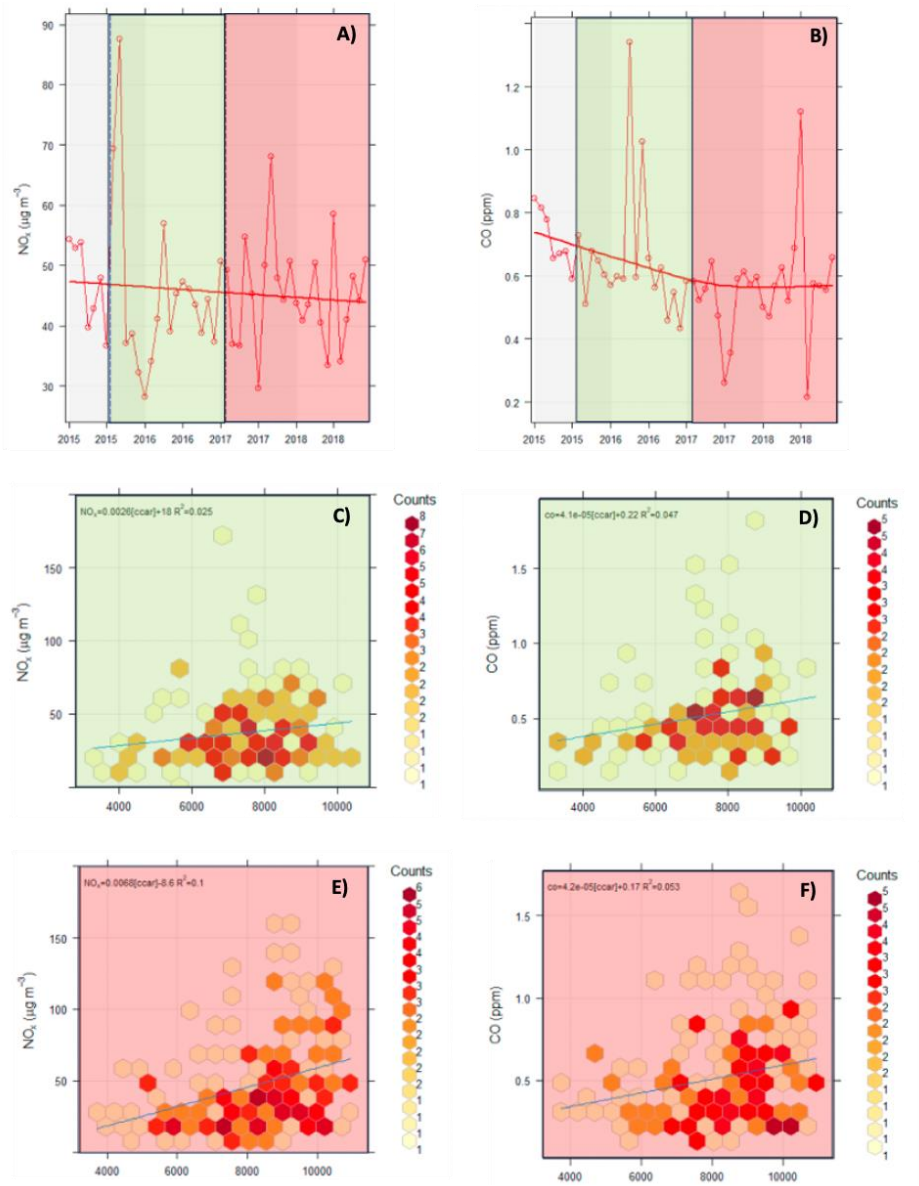

Figure 6. NO_x and CO vehicle related pollution during speed scenarios in the Pinheiros marginal (direction Interlagos, IT): NO_x (a) and CO (b) monthly concentrations and trends (in µg/m³ and ppm), NO_x (c) and CO (d) hourly concentrations (in µg/m³ and ppm) by car flow bins (in number of LDVs/hour, 7 a.m-8 p.m.) during the speed reduction period (from 29/05/2015 to 24/01/2017, green bars), and NO_x (e) and CO (f) hourly concentrations (in µg/m3 and ppm) by car flow bins (in number of LDVs/hour, 7 a.m.-8p.m.) during the speed increase period (from 25/01/2017 to 31/12/2018, red bars).

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3.2. Study Comparison and Research Needs

The literature review carried out in Table 4 shows the relationship between speed reduction measures and the reduction of accidents, as presented in this paper. All the various national and international studies found an average correlation between speed reduction and accident variation: a reduction of ~25% (±15%) of traffic speed limits leads to a reduction of ~31% (±33%) of traffic accidents. Table 4 shows the results of the 29 reviewed studies in a snapshot. In a similar meta-analysis study by Elvik et al. [11], the authors found the following speed and accident reduction values: ~6% (±4%) vs ~27% (±19%). Differences in speed reduction rates are due to differences between legal speed limits and average vehicle speeds. Therefore, reducing road speed limits by 20% leads to a 5% reduction in average speeds [29]. In Table 4, the reduction in traffic is also related to a decrease in pollutant concentrations of ~17% (±77%), as shown in the Pinheiros case study in this paper (24% reduction of NO_X, Figure 6a). In a study carried out by Pérez-Martínez et al. [33] in São Paulo during the COVID-19 episodes, the authors found a good correlation between the reduction of traffic (39%) and the decrease in pollutant concentrations (15-23%).

Table 4. Studies included in the analyses of the relationships between traffic parameters, accident and pollution variations.

Ref.	Transport policy study/ measures and highlights	Time span	Speed reduction	Traffic variation	Accident variation	Pollution variation	Pollutant type
[7]	Speed reduction and pollution	2011-2017	from 120 to 110 km/h in from 90 to 70km/h in urban roads	-15%	-20% -20%	-18%	Fuel consum
[9]	Speed reduction policy on crash accidents	2006	from 60 to 46 km/h in urban roads from 100 to 76 km/h in rural roads		-60% -20%		
[20	Speed reduction policy on crash accidents	2015-2016	from 90 to 70km/h		-22%	-23% -35%	$PM_{2.5}$ CO
[34]	Influence of traffic on PM in Madrid	1999-2001			-30%	-20%	$PM_{2.5}$-PM_{10}
[21]	Speed reduction policy in Barcelona	2008-2009	from 100-120 to 80km/h	-6%	-7%	-5.6% -2.5%	PM_{10} NO_X
[27]	Relationship between speed and traffic fatalities in US	1987-1995	from 100 to 85 km/h rural interstate roads	no traffic variation	-21%		
[35]	Weather, air pollution and traffic accidents in Taipei (Taiwan)	2018			-28%	-13%	$PM_{2.5}$
[36]	Mitigation measures, PM2.5 in Beijing (Olympics)	2007-2011		-50%		-16%	$PM_{2.5}$
[37]	Emission reduction measures during red air pollution alert	2015	emission reduction measures and	-28%		-15%	$PM_{2.5}$

	in Beijing (China)		traffic restrictions				
[28]	Impact of speed variations on freeway crashes in UK	2017	from 80 to 60km/h	-10% -25%	-8% -20%		
[13]	Relationship between speeding and crashes in British Columbia (Canada)	1985-1990	speed reduction from maximum speed limits	-22%	-31% -37%		
[38]	Weather effect on air pollution and traffic in Khuzestan State (Iran)	2008-2015		_ _	-65.4% -5.0%	-25% -25%	NO_x NO_2
[12]	Optimal speed limits to reduce car accidents in Australia	2000-2014	from 80 to 50km/h from 110 to 80 km/h	-38% -27%	-90% -64%		_
[11]	Speed reduction policy and Metanalyses in Oslo (Norway)	2004-2005	from 80 to 60km/h from 90 to 40 km/h	-25% -56%	-67% -94%		
[39]	Teleworking effects on Switzerland cities	2002-2013		-3% -3%		-3% -4%	NO_2 CO
[40]	Air pollution alerts and respiratory diseases in South Korea	2015-2019				-8%	$PM_{2.5}$
[8]	Speed optimization to reduce road accidents and pollution in Shiraz (Iran)	2011	from 82 to 72km/h		-10%	-4%	Several pollutants
[41]	Traffic related pollution in Danish cities (Copenhagen/Roskilde)	2005	from 80 to 40 km/h	-36%		-19% -6%	NO_2 dB
[10]	Accident analyses worldwide	2009-2011	from 70 to 50 km/h from 40 to 36 km/h	-25% -15%	-62% -30%		
[42]	Weather effect on air pollution and traffic in Madrid (Spain)	2006		-27%		-6%	PM_{10}
[33]	Traffic and pollution relationships in São Paulo (Brazil)	2019-2020		-39%		-15%	$PM_{2.5}$

	during COVID-19 lockdown						
				-39%		-23%	CO
				-39%		-15%	NO_2
[43]	Influence of road traffic emissions on air quality in Barcelona (Spain)	1999-2007		-14%		-42%	PM_1
[26]	Speed reduction effect on car accident in Sweden	2014-2015	from 50 to 40 km/h	-4%	-11%		
[44]	Reduction of residential speed limits and traffic behavior in Edmonton (Canada)	2004-2009	from 50 to 40 km/h	-9%	-14%		
[45]	Health effects for $PM_{2.5}$ emission reductions in Beijing	2017		-26%		-32%	$PM_{2.5}$
[46]	War conflict, reduction in traffic volumes and urban pollution in Israel	2005-2006	traffic reduction due to socioeconomic conditions	-40%		-38.5	NO_2
[31]	Risk factors in urban accidents in Zagreb (Croatia)	1999-2000	increase from upper speed limits	_	65%		
[47]	Air pollution in Beijing	1998-2013				-37%	PM_{10}
This study	Reduction of speed limits at marginal roads in São Paulo	2015-2019	from 90 to 70 km/h	-7%	-27%	-24%	NO_X

According to the reviewed studies in Table 4, the assumption between accidents and time (month or year) might not be linear, like the linear regression models applied in this study in Table 3. However, considering traffic volumes from 2011 to 2020, if there was only an average increase of 1.5% annually, the fluctuation in traffic volume might not have caused significant changes in accidents, deaths, and injuries. Furthermore, during this period, the slowdown values in the city changed slightly from 1,112 to 1,170 kilometers per day (5%), showing the small influence of long-term traffic variation on vehicle accidents [22]. Taking theses traffic changes into account, realistic predictions of accidents or deaths can be made accurately. Instead of the linear models in Table 4, we are planning to develop time series models considering traffic exposure and accident rates expressed in terms of number of deaths and injuries per vehicle kilometer. Non-linear models over time can quantify the real impact of various factors: speed, exposure, and other traffic parameters on roads. As such, we need to plan some rigorous statistical models with detailed data on accidents (not just accidents, deaths and injuries per year at aggregate levels).

As shown in Figure 3, there is an overall downward trend in terms of both accidents, injuries, and deaths, as in most of the literature review carried out in Table 4. In these studies, there is a similar international trend regarding traffic pollution. Many factors can contribute to this trend such as technical improvement of vehicles and traffic management. According to the studies reviewed, there is also a relative stable number of accidents and injuries in last five or seven years and there is a strong underlying trend in the data on accidents and pollution. Simply using linear models cannot capture the impact of factors such as speed changes and policies in this study. It is recommended that we consider time series modeling especially during the years following the COVID-19 pandemic, to test changes in traffic behaviors and impacts on new technologies.

4. Conclusions

The results in this study show a clear reduction in the number of accidents without victims on the roads of the city of São Paulo starting in 2010. There was a reduction in accidents on both marginal roads and other roads. However, when there was an increase in speed on the marginal roads, the relevant numbers began to move away. There was an increase in the total number of accidents, including injuries and deaths on the Pinheiros and Tietê marginal roads. A factor that may also have contributed to the increase in accidents would be the difference between the speed limits for light and heavy vehicles in the same and between lanes, since heavy vehicles circulate in the right lane, but this lane is also used by other vehicles (Table 1). The increase in speed had also an impact on air quality worsening in the Pinheiros marginal road (Figure 6).

The results of the model showed that reducing speed on other roads in São Paulo caused a decrease of 30 fatalities per year. Considering that the victims in the marginal roads accounted for ~ 20% of the fatalities in the period studied, ~ 6 deaths could have been avoided annually in the marginal roads. When there was an increase in speed on marginal roads, studies have shown that travel time decreased by 5.5% [20]. However, when traffic accidents occur, the road is blocked due to the rapid assistance of rescue teams. The shorter travel time, which is the main justification for increasing speed, is not advantageous in these situations and the consequences of the accident can include economic losses, injuries, and lost lives. The number of accidents on marginal roads remains high and the problem may be related to the legal speed limit, which is incompatible with WHO and safety guidelines. Increasing speed limits can lead to more congestion events, increasing pollutant concentrations, as shown in Figures 4 and 5.

It can be said that the policy of reducing the speed limit in the city, together with the rest of the measures adopted, came close to the objective of saving lives, meeting the Sustainable Development Goal (SDG) 3.6 of halving the number of deaths from road accidents in 2020 (Figure 2). It is necessary to adopt new policies, such as the review of the speed limit on marginal roads, through technical and scientific knowledge, with the participation of civil society through road education campaigns [31; 45]. It is still necessary to achieve the objective of reducing the number of deaths from traffic accidents by 2030, to a maximum of 3 per 100,000 inhabitants (Figure 2). The latest report released by the traffic engineering company [18] shows that the Pinheiros and Tietê marginal highways continue to be the ones with the most accidents in the city. Other objectives related to compliance with air quality standards must be achieved simultaneously with road safety in the next ten years.

Supplementary Materials: No supplementary materials.

Author Contributions: P.J. Pérez-Martínez: Project administration, Conceptualization, Data curation, Formal analysis, Methodology, Project administration, Writing – original draft, Writing – review & editing. **D. Gonçalves:** Data curation, Formal analysis, Methodology, Writing – _original draft, Writing – _review & editing. **C. Daroncho & J. Dunck:** Formal analysis, Investigation, Validation, Writing – _original draft. **F. Teixeira:** Data curation, Formal analysis, Investigation, Writing – _original draft, Writing – _review & editing. **J. Dias Oliveira:** Investigation, Visualization, Writing – _original draft, Writing – _review & editing. **R.M. Miranda:** Formal analysis, Investigation, Methodology, Writing – _original draft, Writing – _review & editing.

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