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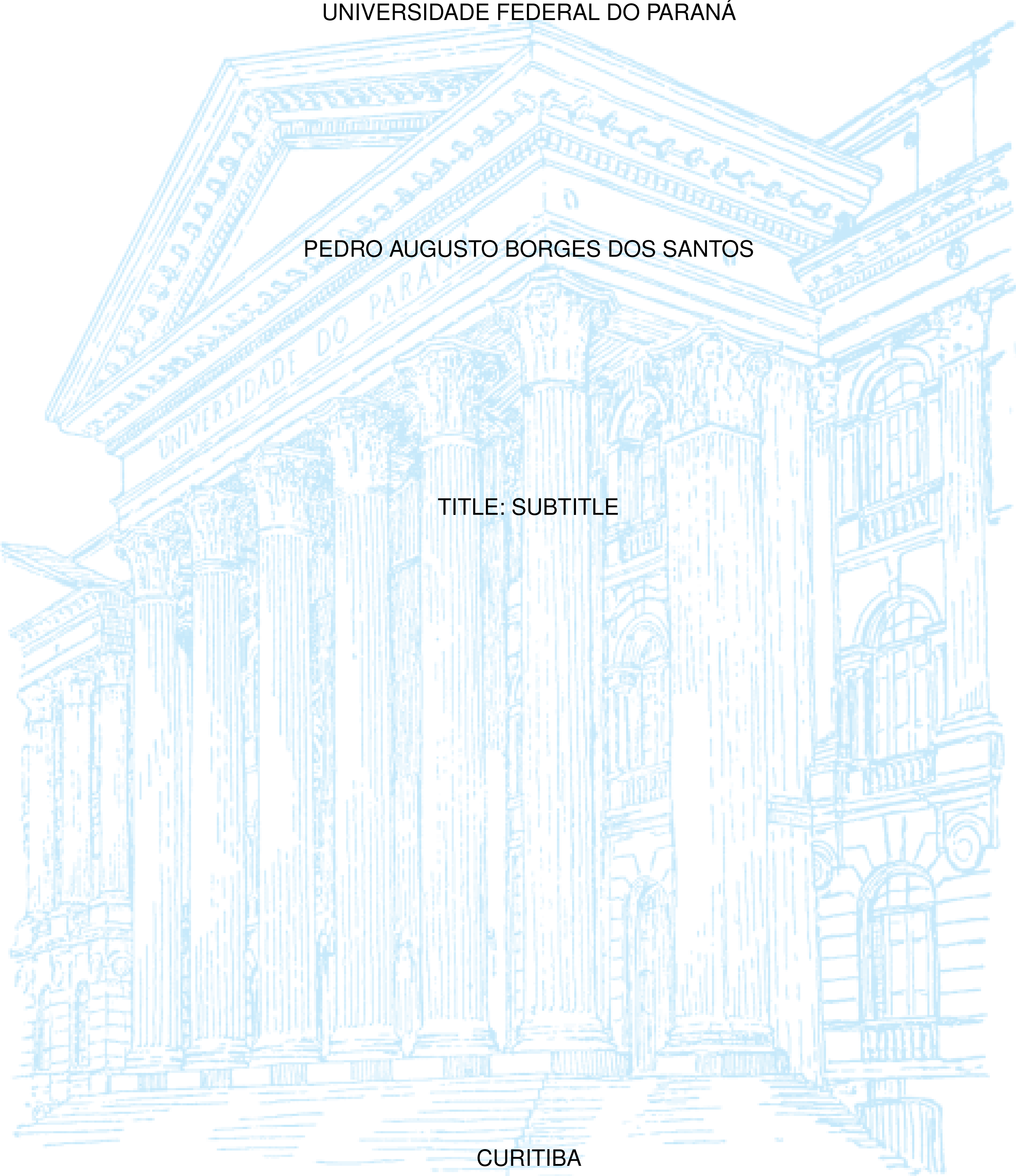

PEDRO AUGUSTO BORGES DOS SANTOS

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2021

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Thesis presented as a partial requirement for the obtaining of a degree in Master of Sciences by the Programa de Pós-Graduação em Planejamento Urbano of Setor de Tecnologia of Universidade Federal do Paraná .

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ABSTRACT

Resumo

Palavras-chaves: Palavras-chave

ABSTRACT

Abstract

Key-words: Key-words

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SUMMARY

1 INTRODUCTION

Very general introduction why the topic of the thesis is relevant.

Road Safety Scenario in the World and in Brazil.

Urban planning having a crucial role on the road safety in cities.

1.1 OBJECTIVES

In the context of the urban planning practices and road safety management, the main objective of this research is to investigate the influence of demographic, socioeconomic, land use and constructed environment on the speeding practices as a risk factor on the frequency and severity of road crashes. The scenario of the study is the city of Curitiba, capital of the state of Paraná, Brazil. The correlation will be analyzed with the use of the Geographically Weighted Regression statistical model.

With the use of speeding data collected from drivers that participated in a Naturalistic Driving Study (NDS) performed in Curitiba, this investigation aims to contribute to the knowledge of its relationship with variables from the built environment (BE). These BE variables are categorized by Ewing and Dumbaugh (2009) in five groups called '5D': density, diversity, design, destination accessibility and distance to transit. In addition to these variables, this study aims to relate the income as a socioeconomic variable to the speeding as well.

As co-benefits in the investigation, this thesis aims to offer some level of insight regarding the development and update of speed control in cities, considering the operational and structural planning guidelines for the road systems and land use. With these factors in mind, it could be possible to present new ideas to the planning practices in Curitiba, regarding mobility plans, master plans and zoning laws.

1.2 JUSTIFICATION

The excess of traffic speed performed by vehicles on urban environments are a main risk factor in the chance and severity of road crashes, considering there is great volume of interaction between motorized and vulnerable users (ELVIK et al., 2009). Considering the direct relationship between the mobility, the land use patterns and the built environment (DE VOS; WITLOX, 2013), it is important to investigate these factors in search of improvements in the management process of the road safety. Speeding, which is on the primary causes for traffic crashes (WHO, 2013) can be better studied and analyzed by the collection of naturalistic data.

Having in mind that most of the traffic crashes and conflicts happens in cities (WHO, 2018), as a consequence of the fast process of urbanization in the last decades, it is crucial to create safer conditions in these localities. In Brazil, the management of the mobility is attributed to the municipalities (BRASIL, 1997). Therefore, the management of road safety, as a task inherent to traffic management, is also an attribution of the municipalities. It is necessary to observe the issues of road safety in cities when conducting the process of urban planning. Having this in mind, it was established laws in which this integration between the planning process by the municipalities and the sustainable mobility are clearly defined: The Statute of the Cities (BRASIL, 2001) and The Law of the Urban Mobility (BRASIL, 2012).

The built environment can affect the traffic safety through three main mediators: the traffic volumes, traffic conflicts and traffic speeds - which can directly affect the crash safety and severity in urban environments (EWING; DUMBAUGH, 2009). Traffic crashes are a final outcome of the problems involving the road safety. Therefore, in order to have a method to analyzed the operational conditions of the traffic safety in cities, it can be beneficial to use a intermediate outcome - or a safety performance indicator (SPI) (BASTOS, 2014) - which can be the amount of speeding that occurs across its territory, in addition to the studies that uses the traffic crashes as dependent variables.

1.3 THESIS STRUCTURE

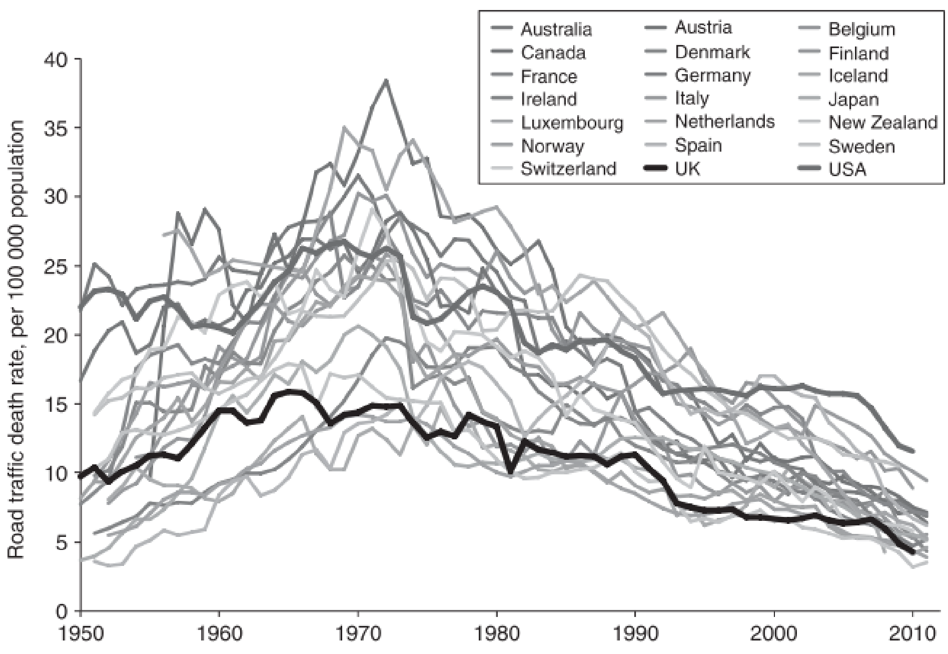
2 LITERATURE REVIEW

2.1 ROAD SAFETY SCENARIO

Road traffic crashes around the world claims more than 1.3 million lives in each year, representing the eighth leading cause of deaths and causing up to 50 million injuries. Low and middle income countries (LMICs), including Brazil, suffers from traffic crashes death rates three times higher when compared to developed countries (WHO, 2018). The increasing number of traffic crashes deaths on LMICs is a consequence of a intense process of motorization that has been occurring in the last decades. To Bhalla and Mohan (2016), it is important to understand the evolution of road safety management on OECD developed countries in order to overcome the road safety problems in LMICs.

Over the last century, the road safety performance of the OECD countries showed a consistent pattern. The road traffic death rate (per 100,000 population) in these countries were rising until the 1960s, as seen in FIGURE 1. After this period, all countries showed a declining pattern, whilst the LMICs still had a rising pattern due to the rapid growth in their motor vehicle fleets. This behavior of rising and declining trend on the road traffic death rate could be explained by three phenomenons: economic determinism, risk substitution and a political shift in the road safety paradigm (BHALLA; MOHAN, 2016).

FIGURE 1 – ROAD TRAFFIC RATES IN OECD COUNTRIES



SOURCE: Bhalla and Mohan (2016).

In the scope of economic determinism, the road traffic deaths are defined as a process related to the country development. The rising pattern is associated with the increase in motorization, and the falling happens after a certain level of development, where the countries have the means to start investing in road safety. But this hypothesis has some flaws. This creates an impression that LMICs are not able to invest in road safety before becoming full developed, which is inaccurate. Also, this idea shifts the focus on investment in direct interventions, encouraging the countries to focus on income growth as a strategy for road safety (BHALLA; MOHAN, 2016).

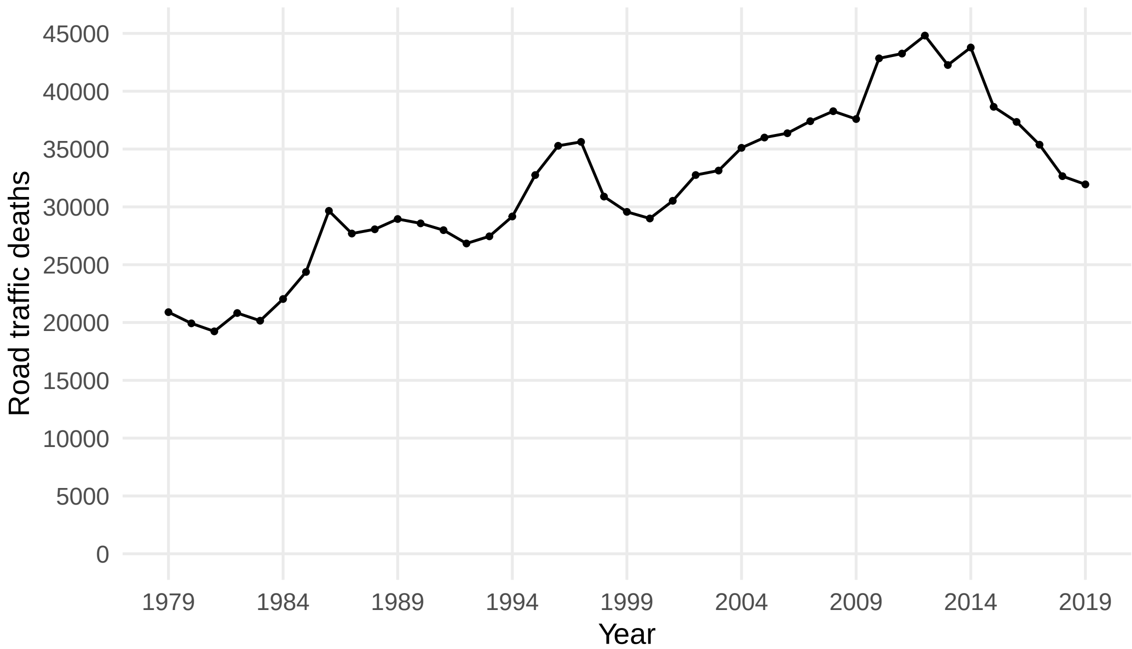
As the mobility in general becomes more motorized towards the use of the car, pedestrians starts transitioning into car users. This circumstance is known as risk substitution, where the increase in car users occurs at the same time as the number of pedestrians declines, lowering the exposure to more severe road traffic injuries like the collision between cars and pedestrians and lowering the number of road traffic deaths. But this phenomenon can be imprecise when considering the motorization of LMICs, in which mass transit, motorcycles and other non motorized transports have a greater role on the vehicle fleet (BHALLA; MOHAN, 2016).

A factor that explains this pattern in a more precise way is the political shift in the road safety paradigm that happened on the OECD countries. Before the 1950s, the belief that drivers were the only responsible for the road crashes lead the discussions regarding road safety. Therefore, most of the interventions in road safety management ignored the design and development of the build environment and the vehicles. Between the 1960s and the 1970s, OECD countries started to regulate transport in order to tackle the road safety problems that were rising, establishing new laws and road safety management institution on national e local levels. (BHALLA; MOHAN, 2016). Analyzing the road safety data from Brazil, it is possible to correlate the actual stage with what the OECD countries passed during the 1970s.

According to WHO (2018), it was predicted that Brazil would had a road traffic mortality rate (number of deaths per 100,000 inhabitants) of 22.5 in 2016, the highest rate between the south american countries. In 2019 (the last entry available by Ministry of Health (2020)), road crashes were responsible for 31.945 deaths. Considering the Decade of Action for Road Safety 2011-2020 (WHO, 2011), Brazil will reach the goal of reducing the road traffic deaths in half (comparing to the number projected for 2020, in case of a rising trend in deaths) by the end of the 2010s. FIGURE 2 has the time series of road traffic deaths in the last decades.

The year of 1979 is the earliest official data entry available. Starting in the 1980s, there is a overall rising trend in the numbers of road traffic deaths that reach its peak in 2012, then it starts declining. In 2010, the year before the Decade of Action, Brazil had 42,844 deaths and reached the max value in 2012: 44,812 road traffic deaths.

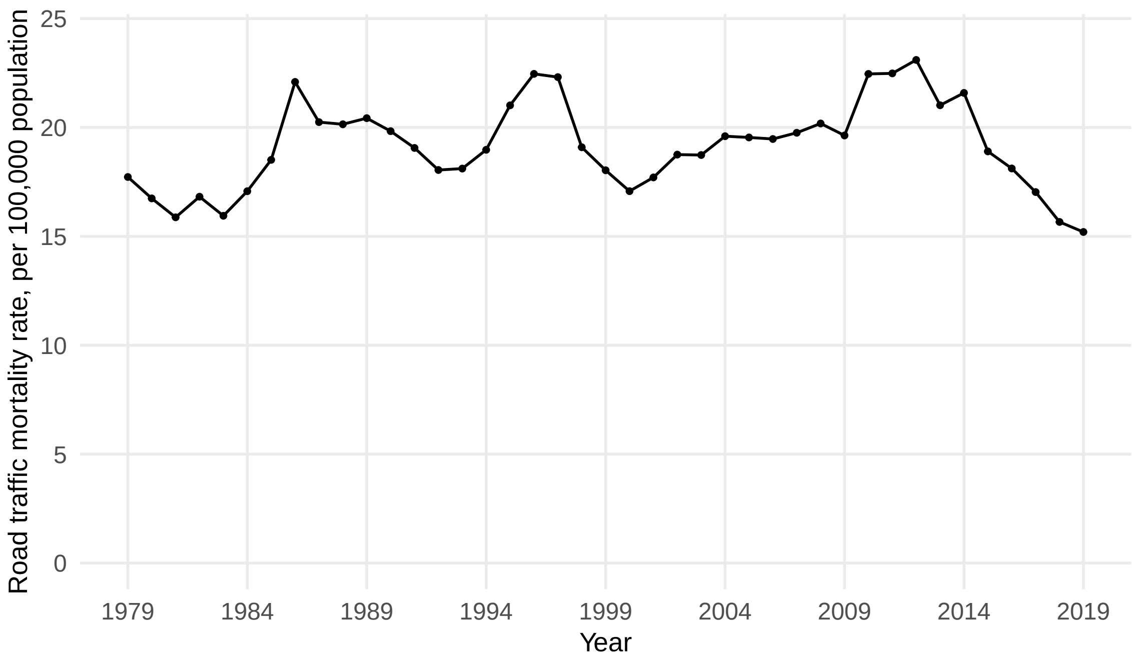
FIGURE 2 – ROAD TRAFFIC DEATHS ON BRAZIL



SOURCE: The Author, based on Ministry of Health (2020).

Almost at the end of the decade the number of deaths declined, reaching 31,945. The next plot (FIGURE 3) shows the mortality rate in Brazil, considering the same time span. In general, it follows the same pattern of the absolute road traffic deaths.

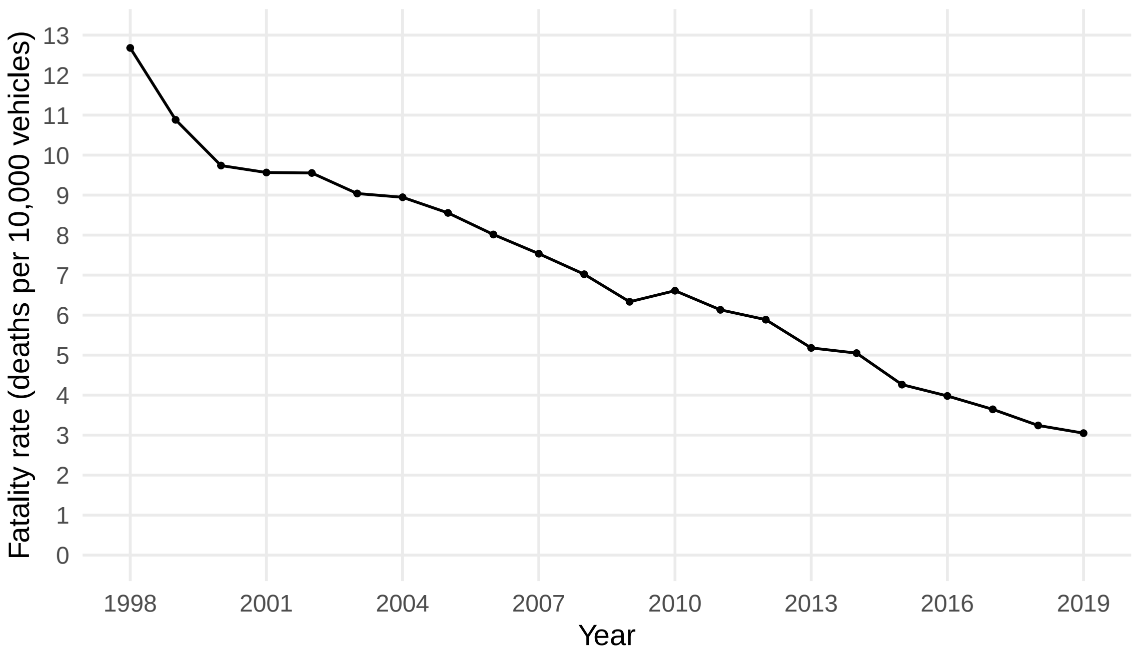
FIGURE 3 – ROAD TRAFFIC MORTALITY RATE ON BRAZIL



SOURCE: The Author (2021), based on Ministry of Health (2020) and Ministry of Health (2021).

The maximum registered mortality rate is 23.1 deaths per 100,000 inhabitants in 2012, the same year which Brazil reached its maximum value for absolute road traffic deaths. Since then the mortality rate has been declining, reaching a rate of 15.2 deaths per 100.000 inhabitants in 2019. In comparison to the OECD countries (FIGURE 1), Brazil presented a strong declining pattern a few years later, after the 2010s. Another indicator that considers the exposition to traffic hazards is the fatality rate - number of deaths per 10,000 vehicles (FIGURE 4). The oldest entry of fleet size in the DENATRAN (2020) database is 1998.

FIGURE 4 – ROAD TRAFFIC FATALITY RATE ON BRAZIL

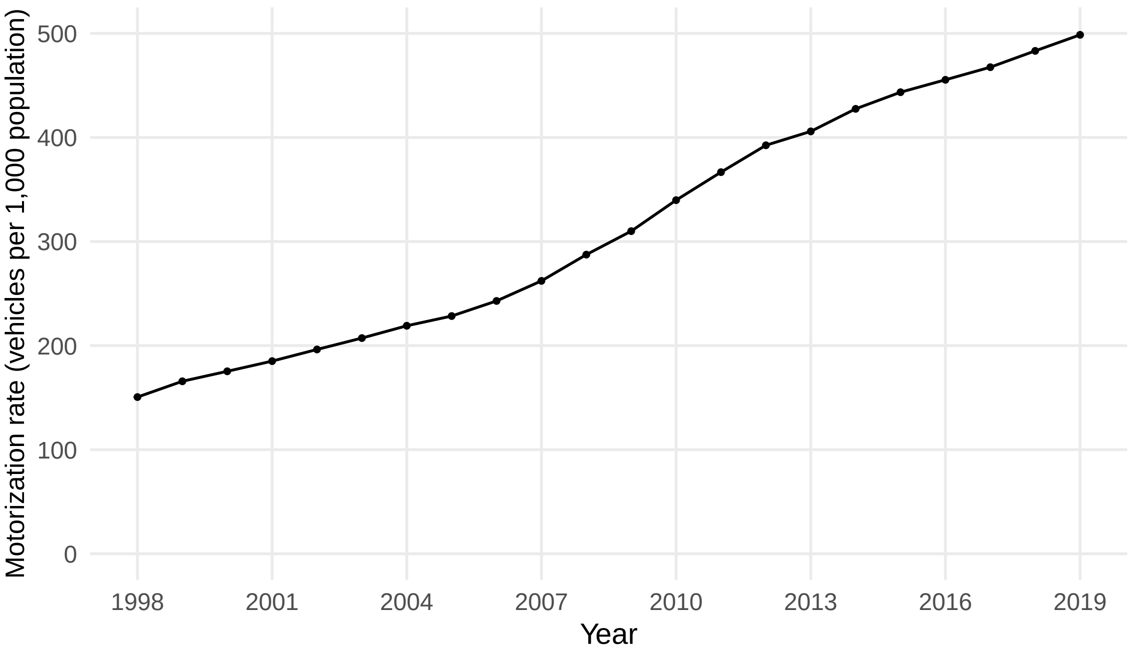


SOURCE: The Author (2021), based on Ministry of Health (2020) and DENATRAN (2020).

Between 1998 and 2019 there is a declining pattern in the fatality rate, starting with 12.7 deaths per 10,000 vehicles in 1998 and ending with 3.0 in 2019, representing a reduction of 76%. This declining pattern can be explained by the continuous rise of the motorization rate (FIGURE 5). In 1998, the motorization rate was 151 vehicles per 1,000 population, increasing to the rate of 499 in 2019. The motorization can be defined as one indicator of the development un the country. Considering the motorization stages defined by Jørgensen (2005), Brazil can be classified nowadays with a exploding motorization.

The first stage of motorization - developing motorization - occurs when a country have a motorization rate between 50 and 100 vehicles per 1,000 inhabitants. This first stage happened in Brazil before 1998. The explosion of the motorization is the second stage, and it happens with a motorization rate of between 300 and 400. The third and last stage is the saturation, and occurs when the motorization rates reaches more than 400 and its tendency stops rising (JØRGENSEN, 2005). Although Brazil has a present motorization rate above 400, it is plausible to affirm that the country still hasn't reached the stage of saturation, considering that the rates are still in a rising pattern.

FIGURE 5 – MOTORIZATION RATE ON BRAZIL



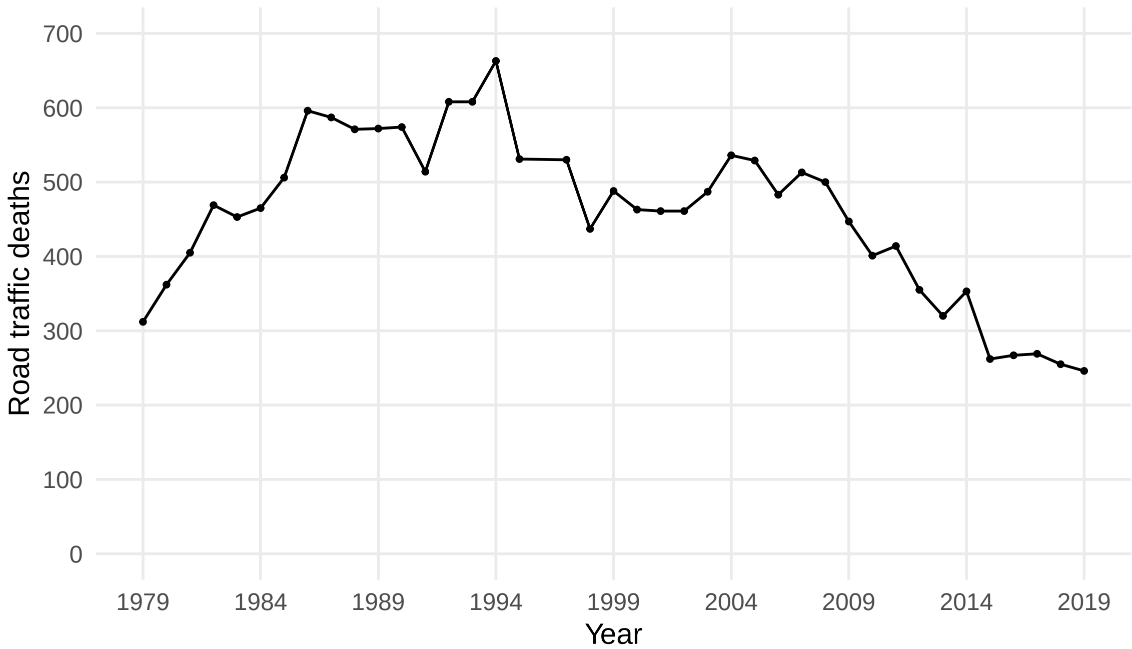
SOURCE: The Author (2021), based on Ministry of Health (2021) and DENATRAN (2020).

In the 1970s, Brazil have undergone through a intense development in the car industry, lowering the price of the vehicles and increasing the development of road infrastructure in cities and rural areas, impacting directly in the rise of the motorization in the country (VASCONCELLOS, 2013). To Harvey (1982), this incentive to motorization created a urban environment that looked to answer the increasing demand of car use. This process lead to worse safety conditions in brazilian cities, specially to non motorized users in the road system.

The variation in the number of road traffic deaths and road traffic mortality heavily influenced by the socioeconomic development and political landscape (FERRAZ et al., 2012). The country had different economical situations between the 2000s and the 2010s. In the period of 2000-2010, Brazil had a continuous growth in the economy, which reflected on the rising pattern of the road traffic deaths and road traffic mortality rates. After the 2010, the country entered in a economic recession, leading to the reduction of these numbers (BASTOS; GARRONCE, et al., 2020). Focusing on the area of study, the road traffic deaths in Curitiba are presented in FIGURE 6.

The tendency of road traffic deaths presented a rising pattern between 1979 and 1994, starting with 312 deaths and reaching a maximum of 663 deaths. Overall, the pattern of the time series started declining after 1995, ending with a minimum value of 246 in 2019. Following the brazilian trend, Curitiba's motorization rate kept rising in the last decades. The increase in motorized transit can lead to more exposition to traffic crashes and injuries, in case road safety interventions are not implanted correctly. The

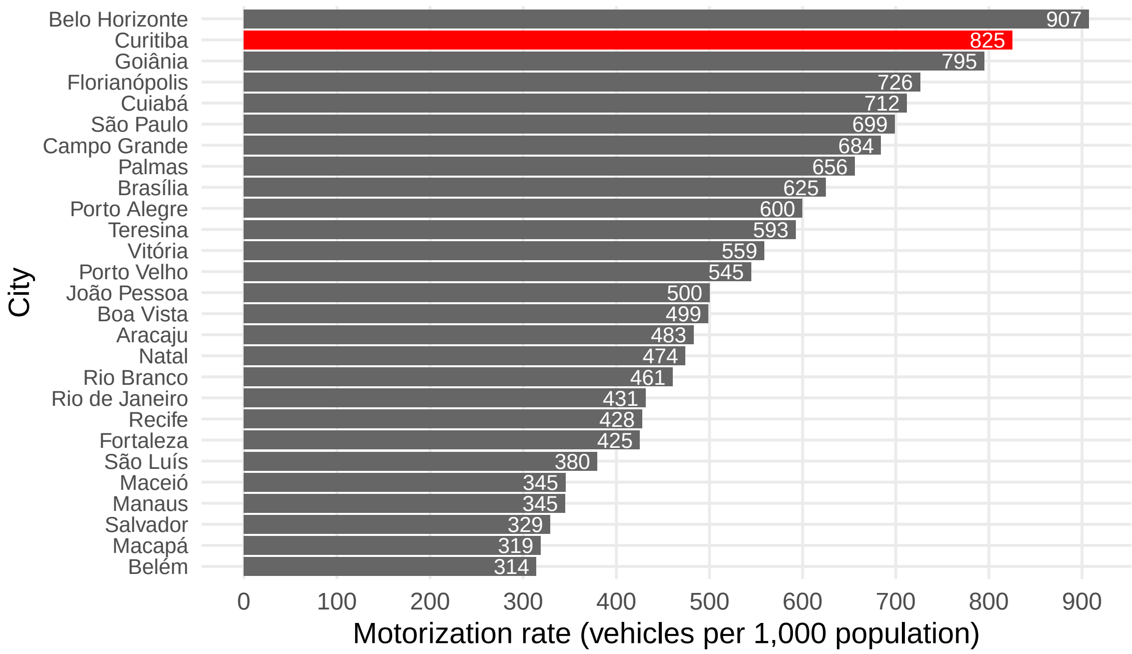
FIGURE 6 – ROAD TRAFFIC DEATHS ON CURITIBA



SOURCE: The Author (2021), based on Ministry of Health (2020).

plot in FIGURE 7 compares the motorization rate between all brazilian states capital cities.

FIGURE 7 – MOTORIZATION RATES ON BRAZILIAN STATES CAPITAL CITIES, IN 2019

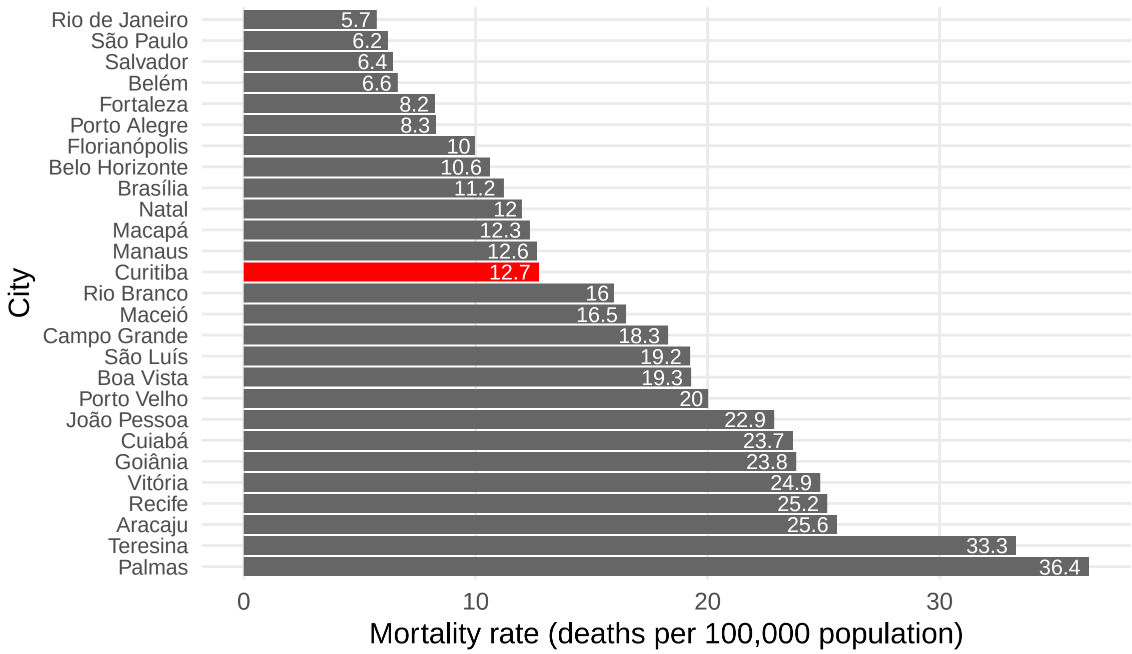


SOURCE: The Author (2021), based on Ministry of Health (2021) and DENATRAN (2020).

Curitiba was, in 2019, the second most motorized capital in Brazil, with a motorization rate of 825 vehicles per 1,000 population, higher than the brazilian average, losing only to Belo Horizonte, which presented a motorization rate of 907 vehicles per

1,000 population. When comparing the road traffic mortality rate (FIGURE 8), Curitiba stays in the 13th place with 12.7 deaths per 100,000 inhabitants, below the brazilian average of 15.2 in 2019. The lowest value of road traffic mortality rate belongs to Rio de Janeiro, presenting a rate of 5.7 deaths per 100,000 population, and the highest belongs to Palmas, with a alarming rate of 36.4.

FIGURE 8 – MORTALITY RATES ON BRAZILIAN STATES CAPITAL CITIES, IN 2019

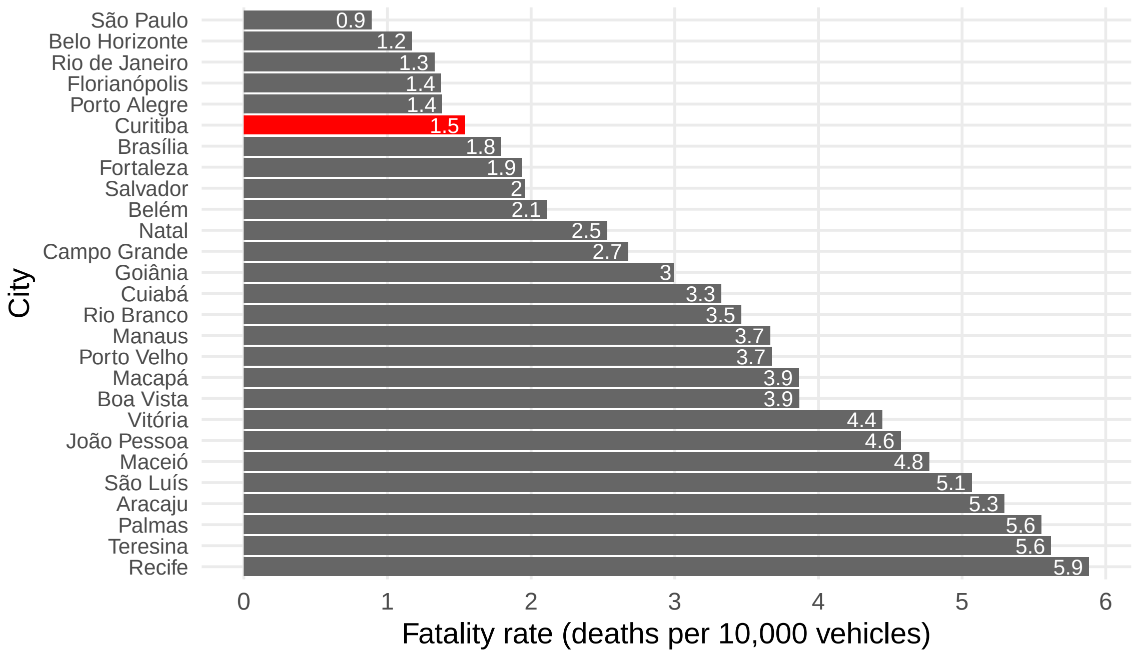


SOURCE: The Author (2021), based on Ministry of Health (2020) and Ministry of Health (2021).

Considering the fatality rate as a road safety performance indicator, FIGURE 9 plot shows that Curitiba have the 6th best performance, with a fatality rate of 1.5 deaths per 10,000 vehicles. São Paulo is the capital with the lowest fatality rate (0.9) and Recife has the highest one (5.9). Observing the fatality rate in Brazil in the same period (3.0), Curitiba is below the country average, with exactly 50% less deaths per 10,000 vehicles. Road traffic crashes and its related injuries have become a serious health problem across brazilian cities. As motorization increases, the number of conflicts and possible crashes increases as well.

Capable interventions in road safety needs to consider traffic deaths and injuries as serious public health problems. Therefore, its control must follow the principle as control of any other public health problem. Road traffic injuries are the result of a complex interaction of multiple factors. These factors can involve human, environmental and vehicle factors, in addition to sociological, psychological, physical and technological factors present the process of traffic crashes. As another health problems, it is possible to analyze road traffic injuries considering three different phases in time: pre-crash, during the crash and post-crash (MOHAN, 2016a).

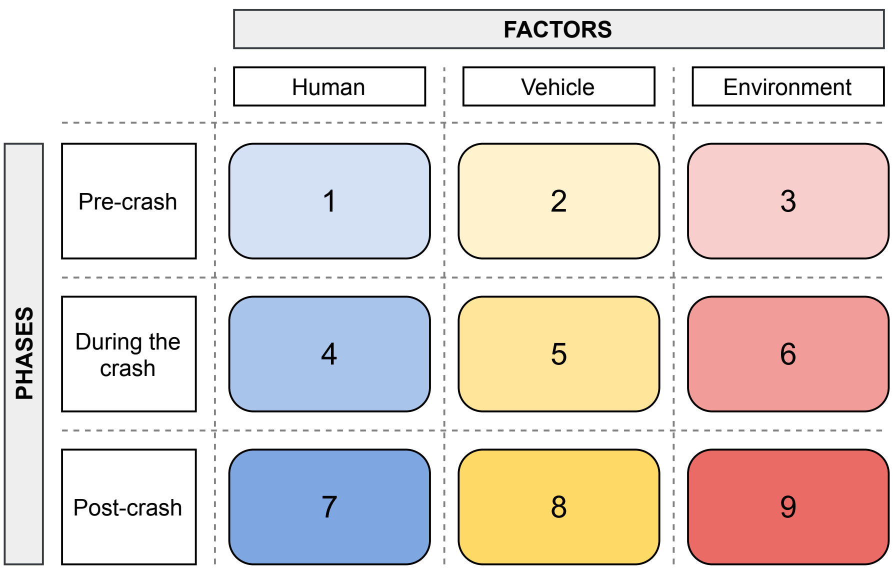
FIGURE 9 – FATALITY RATES ON BRAZILIAN STATES CAPITAL CITIES, IN 2019



SOURCE: The Author (2021), based on Ministry of Health (2020) and DENATRAN (2020).

These distinct phases of time and factors of road traffic crashes can be arranged into a matrix created by Haddon (1980) in order to map all events related to a injury. Named after its inventor, the Haddon matrix (FIGURE 10) consists of two dimensions: one for the time aspect of the event and a second one representing three main discrete factors: human, vehicle and environment. Crossing each step of both dimensions sets nine cells, in which can be made a list of countermeasures to control the damage or to prevent a possible incident, associating these measures to each pair of factors.

FIGURE 10 – HADDON MATRIX



SOURCE: The Author (2021), based on Haddon (1980).

Cells 1, 2 and 3 contains measures towards the prevention of crashes. On a road traffic crash scenario, cell 1 considers the behavior (aggressive driving, driving under influence, distraction) and training of the road users (pedestrians, drivers, motorcyclists and cyclists), cell 2 presents safety interventions related to the vehicles (use of daylight headlights, speed control systems, etc.) and cell 3 contains all elements of the road infrastructure the and build environment that influences directly into the occurrence of this event. Cells 4, 5 and 6 comprehends measures that can reduce the severity during the occurrence of a crash event.

In cell 4 there are measures that include the use of seat belts, helmets and protective clothing. Cell 5 can consider the crashworthiness and safety design of the vehicles and cell 6 includes elements (or lack of elements) that can influence the severity in case of a collision (guard rails, concrete barriers, street furniture, etc.). In the last row are included the measures related to the control and treatment of injuries after the event. Cell 7 presents the treatments related to the victims (hospital care and rehabilitation), cell 8 contain measures related to the safety systems of a vehicle and cell 9 can consider the general management of a crash scene (MOHAN, 2016a).

The road safety problems that happens on urban environments may differ from the ones that happens in major roadways. Even with lower operating speeds, the quantity of conflicts in urban road systems can be considerable higher when comparing to rural roadways, considering the quantity of different motorized and non-motorized transport modes that uses the infrastructure in the same time. Consequently, it is essential to follow requirements for a safe infrastructure. Three main ones are functionality, homogeneity and recognition (SWOV, 2003). Each road on a network needs to have a specific function (balance between mobility and access), with traffic distribution working as intended. Homogeneity consists in reducing the points of conflict between transport modes with great difference of mass and speed. Finally, the situations on traffic should have a level of predictability, passing what behavior should be expected from the road users.

In order to reduce road traffic crashes and possible consequent injuries or deaths, it is relevant to consider the main risk factors that causes and intensify these events. According to WHO (2004), risk in road traffic can be classified into four elements which are directly influenced: exposure, crash involvement, crash severity and post-crash severity. The risk factors that can be classified in these elements also can be distributed within the Haddon matrix as well FIGURE 10. The main risk factors related to the protection of the user consists in the usage of seat belts, helmets, air bags, child restraints and helmets. Focusing on the behavioral factors, the main ones are driving under influence of alcohol and another drugs (DUI), distraction and inattention (SHINAR, 2017).

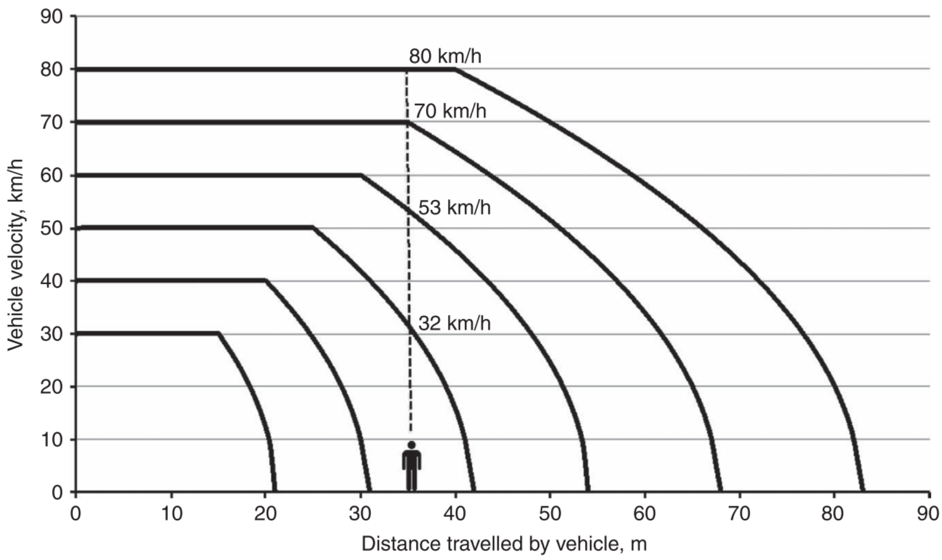
The excess of speed and the speed differential in urban environments are two risk factors that affects the chance of traffic crashes occurrence and the severity of theses crashes. Speeding is a complex phenomenon with multiple causes, consequences and methods of prevention. Given its complexity and spotlight in this thesis, this risk factor will be discussed in the next section (2.2).

2.2 SPEEDING AS A RISK FACTOR

Speeding is one of the primary global causes of road traffic fatalities, affecting two main dimensions: probability and severity (WHO, 2013). The increase in speeds of vehicles is directly correlated to the increase in the occurrence of crashes and its average severity, hence, strongly related to the road safety (MOHAN, 2016b). Another speed-related risk factor is the speed differential, which is the speed deviation from the average operating speed (SHINAR, 2017). Ferraz et al. (2012) defines speeding as a inappropriate speed, leading to more conflict and crashes in certain traffic conditions.

The excess of speed can influence three main factors in the occurrence of a traffic conflict: reaction time, braking distance and force of impact, which is directly correlated to the severity of injuries (MOHAN, 2016b). Reducing the speed helps the driver to increase its reaction time, also helping the driver to take a correctional action to anticipate crashes (ELVIK et al., 2009). Regarding the braking distance, lower speeds reduces the distance necessary to fully stop the vehicle. FIGURE 11 shows the reaction time of a vehicle added to the braking distance, resulting in the distance travelled by the vehicle. The dashed line represents a pedestrian standing 35 meters from the traveling vehicle.

FIGURE 11 – RELATIONSHIP BETWEEN SPEED AND BRAKING DISTANCE



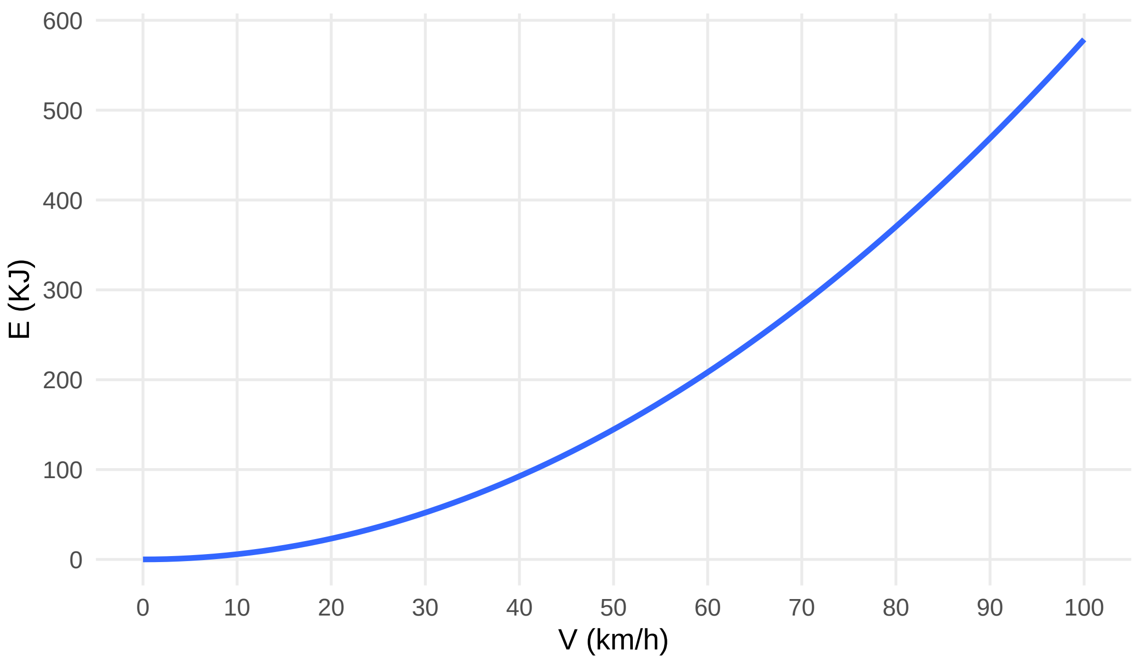
SOURCE: Mohan (2016b).

The horizontal lines from the plot shows the cruising speeds of the vehicle before they start breaking, longer lines at higher speeds represents greater reaction times. In this scenario, only speeds equal or below 40 km/h are able to avoid a collision with the pedestrian. As the vehicle speed rises, the impact speed rises as well. This leads to the increase in force of impact between vehicles and pedestrians. The severity of injuries sustained by pedestrians depends on the energy of impact - the kinetic energy transferred to the human body. This energy of an object (the vehicle), directly related to its velocity and mass, detailed in the following equation:

$$E = 0.5 \times MV^2; \tag{2.1}$$

where E is the kinetic energy, M is the object's mass and V is the velocity of the object. The plot in FIGURE 12 shows the increase in kinetic energy, considering an average car mass of 1,500 kg (ZERVAS; LAZAROU, 2008) and speeds varying between 0 and 100 km/h. The quantity of energy doubles when the speed changes from 40 km/h to 60 km/h, and almost triples at 70 km/h. This variation shows how the reduction of speed limits can greatly change the energy of impact.

FIGURE 12 – RELATIONSHIP BETWEEN SPEED AND KINETIC ENERGY

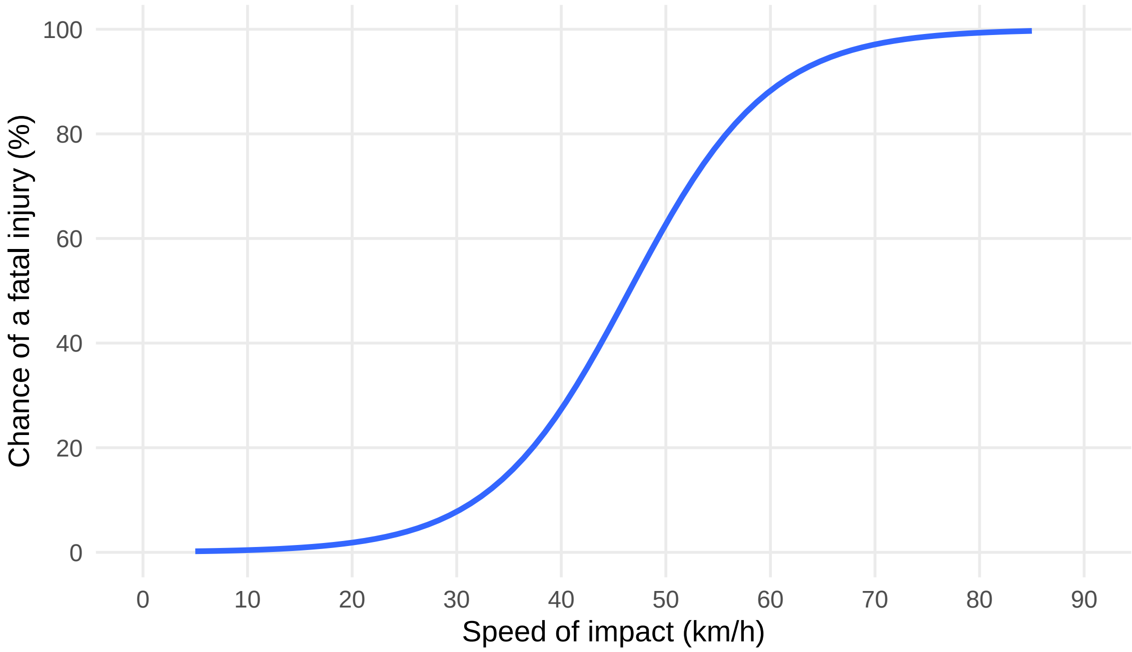


SOURCE: The Author (2021).

Considering the event of an impact between a front of a car and a pedestrian, Ashton (1980) presented the relationship between the impact speed and the percentage of fatally injured pedestrians per speed window, represented in the plot of FIGURE 13. The curve shows how a reduction from 60 km/h to 40 km/h on the speed of impact can reduce the chance of a fatal injury from 90% to 30%, approximately. Reducing the speed of impact to 30 km/ will reduce the chance of a fatal injury to approximately 10%.

In general, as the speed of impact rises, the chance of a fatal injury rises too, with a greater variation between speeds of 30 km/h and 60 km/h.

FIGURE 13 – PROBABILITY OF PEDESTRIAN FATALITY AT DIFFERENT IMPACT FATALITIES



SOURCE: The Author (2021), based on data from Ashton (1980).

The risks highlights the importance of proper speed management in road traffic, specially in urban environments. Roadways have higher operational speeds, but cities contains a more expressive interaction between motorized and vulnerable users, in which lower speeds can still represent a risk to pedestrians and cyclists. One method to manage the operating speed is the enforcement of speed limits. It is recommended a speed limit of 50 km/h in urban arterial roads, and a limit of 30 km/h in roads with a high flow of pedestrians and cyclists (WHO, 2008). Reducing the mean speeds can greatly favor the decline in fatal, non fatal and property damage only (PDO) road crashes (ELVIK, 2013).

The operating and mean speed of the road traffic depends on how the drivers chooses the speed. This choice is related to the power and stability of the user's vehicle, to road and traffic conditions,to driver's perception of safety, to the level of enforcement, travel motivations, personal characteristics and behavior of other drivers (MOHAN, 2016b; SHINAR, 2017). Considering all theses factors, it is not effective to rely only on traffic limits to prevent speeding. If the design speed of a road is higher than the speed limit and the road traffic has a low density, it is more difficult to enforce a the desired limit. The difficulty to enforce the speed limits may be higher to LMICs, which have less resources to adopt the proper road designs policies and enforcement levels required to this task (MOHAN, 2016b).

In TABLE 1 is presented a few groups of factors affecting speeding and speed choice, with its categorization based on the three main discrete factors of road crashes established by Haddon (1980): human, vehicle and environment. Analyzing the human (or driver) factors, the background characteristics includes the level of experience, education and training of the drivers. Demographic characteristics considers the groups of age, sex and income. The general health of the driver, including the conditions of vision, hearing and sleep patterns are included in the physiological factors. The last factor in the human group - attitudes, beliefs and motivations considers how the road user perceives the control and norms present in traffic situations (RICHARD; CAMPBELL; LICHTY, et al., 2013).

TABLE 1 – FACTORS THAT AFFECTS SPEEDING AND SPEED CHOICE

Human	**Vehicle**	**Environment**
Background characteristics	Type/Size	Road elements
Demographic characteristics	Engine power	Weather
Physiological factors	Comfort	Traffic conditions
Attitudes, beliefs and motivations	Field of view	Surroundings
	Age	Speed Enforcement

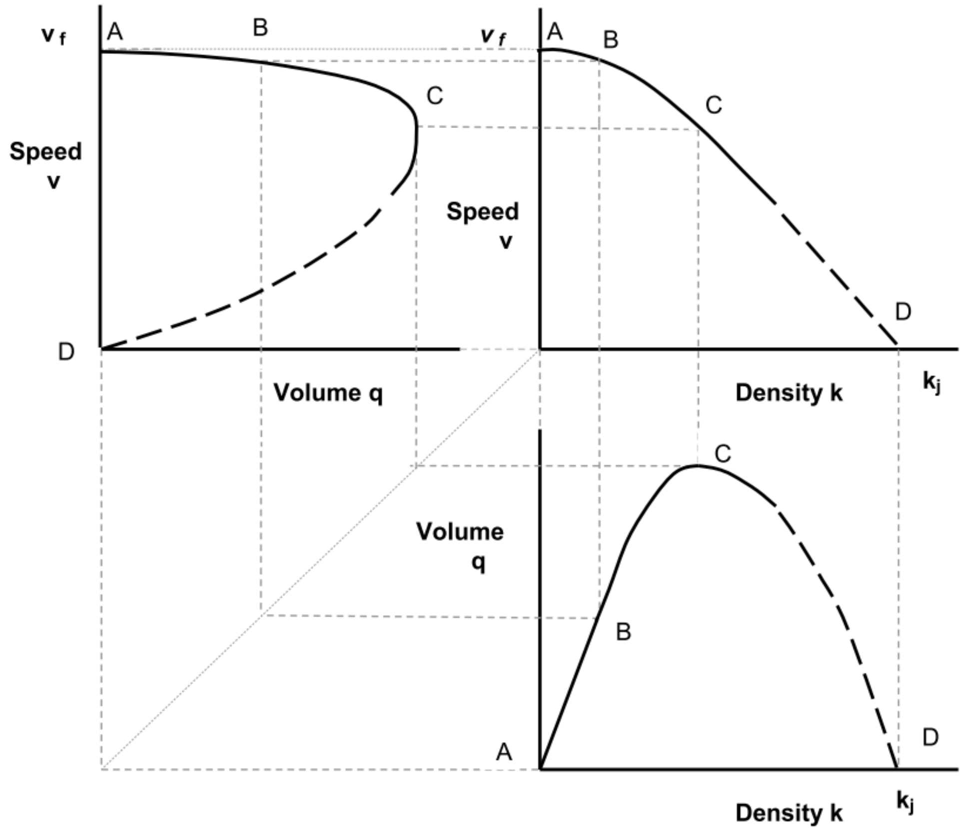
SOURCE: The Author (2021), based on Richard, Campbell, Lichty, et al. (2013), Shinar (2017) and WHO (2008).

All these human factors are related to the general driver profile and its performance when driving the car. as an example of the influence in the individual differences present in the demographic characteristics, younger drivers are more likely to speed than mature and older drivers, and men are more likely to speed than women (SHINAR, 2017). The vehicle characteristics also affects the speed choice of the user. The type, engine power, comfort, field of view and age of the vehicle can affect the possibility to the driver reach the desired speed.

The environmental factors affecting speed choice consists of all the elements external to the vehicles and are greatly related to how the driver behaves and to how the vehicle is able to operate. Road elements can include the general characteristics of a road layout, quantity and type of intersections, design and level of maintenance, based on its alignment, gradient, width, surface condition, geometric pattern and road lightning. The presence of intersections and the high density of traffic controls the operating speeds in urban areas (MOHAN, 2016b). Weather can also affect how the driver will chose his speed, considering its effects on surface conditions (dry, wet, ice) and natural light.

The speed and speed variance are to a certain extent determined by the traffic flow regime (SHINAR, 2017). Depending on the level of flow and density or any other operational condition of the traffic, the driver cannot be able to reach a higher desired speed, removing his ability to have a opportunity to speed (RICHARD; CAMPBELL; LICHTY, et al., 2013; BASTOS; SANTOS, et al., 2021). The plot in FIGURE 14 illustrates the relationship between speed, density and volume (or flow) in uninterrupted flow conditions of a certain road. This type of flow occurs in areas without interference from external factors, like intersections or crossings (GREEN; LEWIS, 2020).

FIGURE 14 – RELATIONSHIP BETWEEN TRAFFIC SPEED, VOLUME AND DENSITY



SOURCE: Green and Lewis (2020).

When density and volume are at its lowest value, the road user can reach higher speeds without having traffic to prevent it (point A). Between points A and B, volume and density starts to rise and speeds decline a little, but still is high enough to be characterized as a free flow speed. In this situation, the driver starts to experience a lack of manoeuvre freedom, but it still have the opportunity to speed. At the highest level of density (point C), speed declines as density rises. Between C and D, density rises until it reaches its maximum value, reducing overall speeds and volume (GREEN; LEWIS, 2020). In this last stage, the drivers have less flexibility to choose a desired speed, having to operate in a forced flow condition.

Established as an environmental factor affecting speeding choice (TABLE 1), the surroundings of the road, including equipments and some traffic calming techniques like gateway treatments, can be perceived by the driver as elements that gives hints to avoid higher speeds (WHO, 2008). Overall, the built environment and its five elements - density, design, diversity, destination accessibility and distance to transit - can be perceived as environmental factors which affects the road safety, through the relationship to the numbers of road crashes and occurrence of speeding. These characteristics are better explored in the next section (2.3).

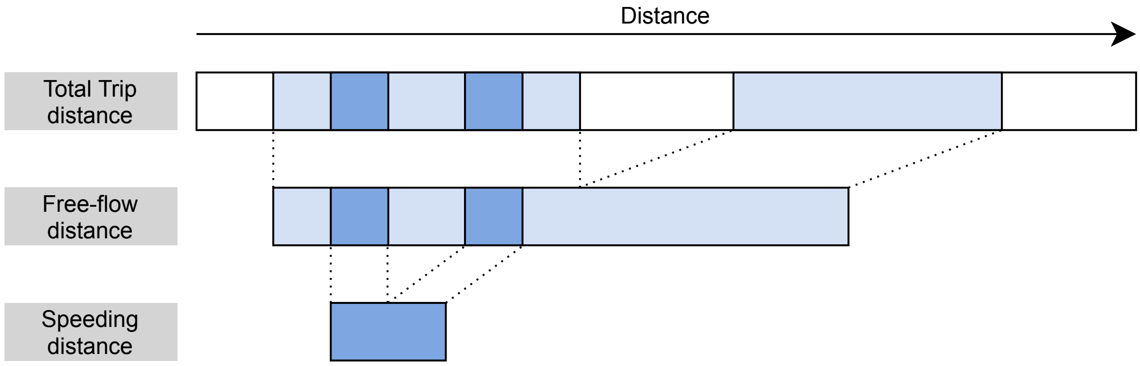
In order to collect speeding data, it is important to establish what defines speeding and to identify a measure of exposure to speeding. To Richard, Campbell, Brown, et al. (2013), defining speeding and its constitution is one of the key challenges of speeding studies. The authors presented five distinct approaches for defining speeding: ad hoc, analytical, kinematic, psychological and behavioral. The ad hoc approach assumes that the fastest driving in a sample if a proxy for speeding and considers the top X% of speeds above the posted speed. Although this approach can provide sufficient data for analysis, the speeding collected may be not related to behavior or safety.

The analytical approach fixes a criterion relative to the speed limit (+ X% or + X km/h). It is a simple method to implement, but can miss some factor related to road type and overall speed level. The analytical approach is used in this work and its process of implementation is detailed in section 3.2. The kinematic approach considers the driving environment and its operational conditions, in order to connect the speed behavior to specific situations. This approach requires a certain level of quantity and quality of GIS data to support it. The psychological approach is based on what the driver considers to be speeding, providing insight into factors that are related to individuals perception of speeding. The necessity of additional previous information about the speeding beliefs and attitudes of the drivers can be a disadvantage of this approach. At last, the behavioral approach sets four speed bands to describe different behavior in each one, related to the chosen speed by the driver (RICHARD; CAMPBELL; BROWN, et al., 2013).

The operational aspects of urban road traffic (mostly in interrupted flow conditions) arbitrary reduces the amount of speeding being measured. To address this problem, it is necessary to extract the free-flow situations of the trip from the total trip distance, removing sections in which drivers had no opportunity to speed. This process of extracting parts of the trip in which the driver is exposed to speeding is presented in FIGURE 15. Therefore, the actual measure of speeding is distance performed in speeds above the posted speed compared to the distance performed in free-flow speed. This process was applied in this work and it is described in section 3.2.

The data collected also depends on the method applied. The collection of speed data can be done with the use of speed traps - fixed or mobile (HIDALGO-SOLÓRZANO et al., 2020; WHO, 2008), the analysis of road crashes reports (WATSON et al., 2015), roadside observational studies (SHINAR, 2017), questionnaires (DINH; KUBOTA, 2013), smartphone data (WARREN; LIPKOWITZ; SOKOLOV, 2019) and GPS data collection (MORENO; GARCÍA, 2013; WANG et al., 2018). Studies that uses naturalistic data

FIGURE 15 – EXTRACTION OF FREE-FLOW AND SPEEDING EPISODES FROM TRIPS



SOURCE: The Author (2021), based on Richard, Campbell, Brown, et al. (2013).

includes the capture video data from the drivers and GPS can relate the speeding action registered with a certain behavioral action from drivers (BASTOS; SANTOS, et al., 2020) and environmental factors (MORENO; GARCÍA, 2013). The speeding data collected from driving simulation studies also can be correlated with other environmental or behavioral factors (YADAV; VELAGA, 2020). The aspects of naturalistic driving studies and its comparison to other methods will be better explored in the section 2.4.

Knowing the factors that affects speeding and the methods to collect and analyse speeding data, it is possible to create countermeasures to this risk factor in road traffic crashes. Following the categories established by Haddon (1980) and presented in TABLE 1, these countermeasures can be classified into behavioral (human), vehicular and environmental approaches. Behavioral approaches includes the education and training to teach speed awareness to drivers. Enforcement is also a behavioral approach. Enforcement by the police or other traffic authority is related to a greater rate of speed limit compliance, but it is a highly localized measure (SHINAR, 2017).

The vehicle approach to intervene in speeding practices includes speed limits and advisory systems in cars. Environmental approaches are consisted of direct changes in infrastructure, including traffic calming measures, and policy approaches, including the establishment of speed limits and administrative actions. Speed bumps, lane narrowing, roundabouts and rumble strips are some of the traffic calming techniques that are capable to reduce speeds in urban environments (WELLE et al., 2016). Other key elements of urban design also can intervene in the practice of speeding, including street block sizes, road network connectivity and road lane width.

2.3 ROAD SAFETY PERFORMANCE AND THE BUILT ENVIRONMENT

Present all the available and used indicators. Guide the literature review based on the indicators (which articles are using the same indicators and why - ewing ...)

add ewing, dumbaugh scheme of BE, mediators and safety.

Add description from urban elements (reports passed form Tiago)

Master plan, mobility planning and zoning laws (try to focus on the mobility and road safety, maybe a brief history). –> relating to the previously described elements

2.4 NATURALISTIC DRIVING STUDIES

- Introduce the Naturalistic Driving Studies as an alternative for the analysis of behavior. Describe multiple international NDS programs, reference the NDS that analyses the speeding. (this part needs to be well described.)
- categorize the nds programs and compared with the method used in this work. (maybe construct a table)
- Focus on authors that used NDS to study speeding.

2.5 GEOGRAPHICALLY WEIGHTED REGRESSION

Regression analysis is a tool to investigate the dependency between variables and to predict future parameters based on previous ones. This type of statistical analysis can show the relationship between dependent variables (road accidents or speeding) and independent variables (land use, road design etc.) (LINDLEY, 1987). In investigation of the effects of the constructed environment on the occurrence of crashes in urban areas, negative binomial regression is a traditional model used (WEI; LOVEGROVE, 2013; ZHANG et al., 2014). But the quality of this model is limited by the incapacity of analyzing the spatial dependency and heterogeneity expected to happen on road safety factors related to the urban environment (OBELHEIRO; SILVA; NODARI, 2019).

To overcome this limitation, the Geographically Weighted Regression (GWR) allows the exploration of relationship between variables on a spatial nonstationarity context. The spatial nonstationarity is a scenario where it is assumed that parameters are not constant across the space. In this thesis context, these parameters are the occurrence of speeding across Curitiba's territory. A global regression model may be incapable of explaining the relationship between sets of variables with a acceptable level of precision in this scenario. The GWR model considers that the nature of the model must alter over space to reflect the structure within the data, allowing the actual parameters for each location in space to be modeled and mapped (BRUNSDON; FOTHERINGHAM; CHARLTON, 1996).

The basic form of GW linear regression is based on the following equation:

$$y_i = \beta_{i0} + \sum_{k=1}^{m} \beta_{ik} x_{ik} + \epsilon_i; \tag{2.2}$$

where y_i is the dependent variable (speeding) at location i, x_{ik} is the value of the kth independent variable at location i, m is the number of independent variables, β_{i0} is the intercept parameter at location i, β_{ik} is the local regression coefficient for the kth parameter at location i and ϵ_i is the random error at location i. The GWR model depends on a spatial weighting function called w_{ij} that controls the contribution of the point j on the calibration of a model for point i. The spatial weighting function represents the idea that for each point i there is a bump of influence around it. Considering this "bump", observations closer to i have more influence in the estimation of i's parameters (BRUNSDON; FOTHERINGHAM; CHARLTON, 1996; GOLLINI et al., 2013).

In the context of a multivariate GW model, these influences are calculated by a weighted least squares approach, described on the following equation:

$$\hat{\beta}_i = (X^T W(u_i, v_i) X)^{-1} X^T W(u_i, v_i) y; \tag{2.3}$$

where X is the matrix of the independent variables with a column of 1s (ones) for the intercept, y is the dependent variable vector, $\hat{\beta} = (\beta_{i0}, ..., \beta_{im})^T$ is the vector of $m+1$ local regression coefficients and W_i is the diagonal matrix denoting the spatial weighting (w_{ij}) of each observed data for regression point i at location (u_i, v_i) (defined by the selected kernel function) (GOLLINI et al., 2013). The spatial weighting function is also known as the kernel function. This function can have multiple configurations, including Gaussian, Exponential, Boxcar, Bisquare and Tricube configurations, detailed on TABLE 2.

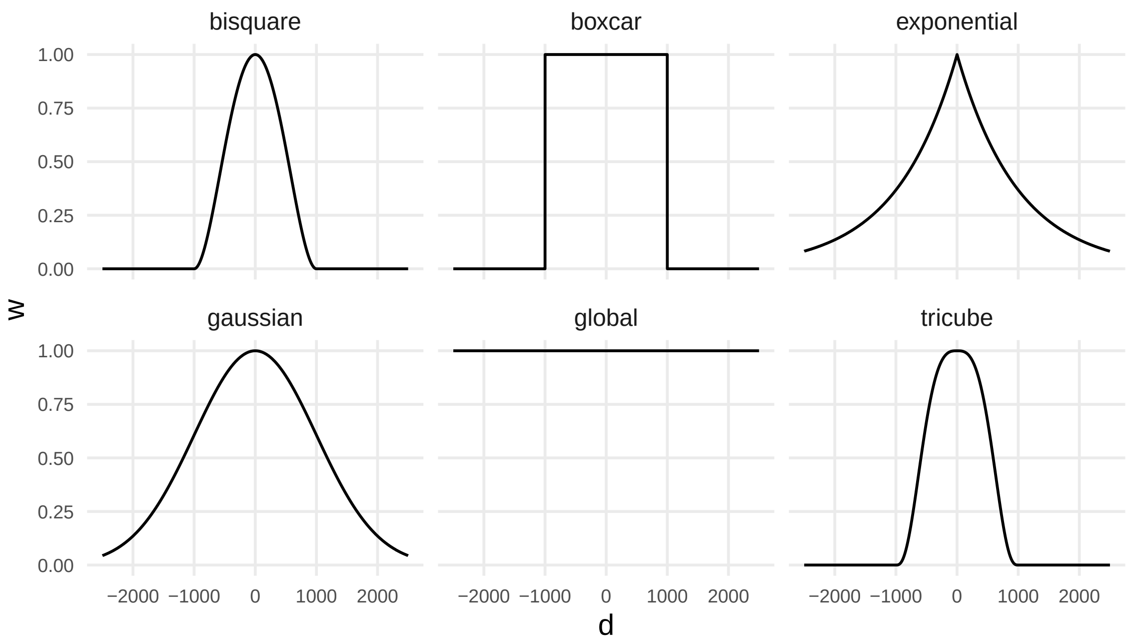
TABLE 2 – AVAILABLE KERNEL FUNCTIONS

Model	**Equation**
Global Model	$w_{ij} = 1$
Gaussian	$w_{ij} = \exp(-\frac{1}{2}(\frac{d_{ij}}{b})^2)$
Exponential	$w_{ij} = \exp(-\frac{\lvert d_{ij}\rvert}{b})$
Boxcar	$w_{ij} = \begin{cases} 1 & \text{if } \lvert d_{ij}\rvert < b, \\ 0 & \text{otherwise} \end{cases}$
Bisquare	$w_{ij} = \begin{cases} (1-(d_{ij}/b)^2)^2 & \text{if } \lvert d_{ij}\rvert < b, \\ 0 & \text{otherwise} \end{cases}$
Tricube	$w_{ij} = \begin{cases} (1-(\lvert d_{ij}\rvert/b)^3)^3 & \text{if } \lvert d_{ij}\rvert < b, \\ 0 & \text{otherwise} \end{cases}$

SOURCE: Gollini et al. (2013)

The distance between observations i and j is defined by d_{ij}, inside a chosen b bandwidth, which is the key controlling parameter in all kernel functions. The optimal bandwidth can be estimated by a cross-validation function, a process that will be detailed in the section 3.3. FIGURE 16 presents the plot of the kernel functions, for a generic bandwidth $b = 1000$, where w is the weight and d is the distance between two observations. As the plot shows, the global kernel function represents a global linear regression, where all the variables are constant across the space.

FIGURE 16 – KERNEL FUNCTIONS PLOT



SOURCE: The Author (2021), based on Gollini et al. (2013).

In addition to the different types of kernel functions, the GWR has multiple configurations based on the type of regression: negative binomial (GWNBR), Poisson (GWPR) and Gaussian, which is the basic form of linear GWR described on EQUATION 2.2. The GWNBR and GWPR models were used by Obelheiro, Silva, and Nodari (2019); Obelheiro, Silva, Nodari, et al. (2020) and Yu and Xu (2017) to study the impacts of the built environment on the occurrence of road crashes inside urban areas.

In conclusion, GWR is a method that enables the exploration of findings that might otherwise be missed if only a global regression method is applied. It is always important to really check if the GWR model will describe the data better than a global regression model comparing the results from both. All the process of constructing a GWR model and its parameters for this work is described in section 3.3.

3 METHODS

3.1 NATURALISTIC DATA COLLECTION

3.2 DATA PROCESSING

3.3 GEOGRAPHICALLY WEIGHTED MODEL

4 ANALYSIS AND RESULTS

5 CONCLUSIONS

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