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Article

Road’s mortality prediction for the most vulnerable users in the context of the COVID-19 pandemic in Santiago de Cali, Colombia

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Abstract: The purpose of this study is to predict the frequency of mortality from urban traffic injuries for the most vulnerable road users before, during and after the confinement caused by COVID-19 in Santiago de Cali, Colombia. Descriptive statistical methods were applied to the frequency of traffic crash frequency to identify vulnerable road users. Spatial georeferencing was carried out to analyze the distribution of road crashes in the three moments, before, during, and after confinement, subsequently, the behavior of the most vulnerable road users at those three moments was predicted within the framework of the probabilistic random walk. The statistical results showed that the most vulnerable road user was the cyclist, followed by motorcyclist, motorcycle passenger, and pedestrian. Spatial georeferencing between the years 2019 and 2020 showed a change in the behavior of the crash density, while in 2021 a trend like the distribution of 2019 was observed. The predictions of the daily crash frequencies of these road users in the three moments were very close to the reported crash frequency. The predictions were strengthened by considering a descriptive analysis of a range of values that may indicate the possibility of underreporting in cases registered in the city’s official agency. These results provide new elements for policy makers to develop and implement preventive measures, allocate emergency resources, analyze the establishment of policies, plans and strategies aimed at the prevention and control of crashes due to traffic injuries in the face of extraordinary situations such as the COVID-19 pandemic or other similar events.

Keywords: mathematics; pandemic; road users; lockdown; spatial analysis

1. Introduction

Since the COVID-19 outbreak was classified as a pandemic (WHO, 2020), non-pharmaceutical strategies have been proposed to mitigate and delay its spread (Georgeades, et al., 2023; Patiño et al., 2020). In this context, mandatory preventive isolation was established in Colombia, including the closure of establishments and the suspension of public transportation, impacting mobility patterns, especially in the urban environment with a significant reduction in vehicle flow and an increase in traffic speed, with consequences in fatal traffic crashes (MEN, 2020). During the confinement period, all countries reported a decrease in the number of fatalities in their reports, finding the containment measures established in response to the COVID-19 pandemic as one of the main reasons for this decrease. However, a more detailed study of the situation showed that the number of deaths on the roads did not decrease in the same proportion as traffic was reduced (Adanu, et al., 2022; International Transport Forum, 2020; Marshall, et al., 2023; Soltani, et al., 2023).This disproportion was identified when the increases in the average speeds and the severity of registered traffic crashes were analyzed, making it necessary to carry out another type of analysis that considered the confinement measures and their impact on traffic in each country. Another emerging aspect was the increase in the number of cyclists and motorcyclists because of the isolation measures that modified the capacity of public transport due to COVID-19 (Alnawmasi and Mannering, 2023; Demir, 2024; International Transport Forum, 2020; Scorrano and Danielis, 2021). Also, it was observed that the affected cities, districts, states, and countries, had to change or adjust the containment strategies taken in the crisis of the virus spread as an increase in the number of infected people and deaths was triggered, especially in the initial and acute phase of the COVID-19 pandemic. The above allowed in few cases to replicate the same strategies, especially for public transportation systems (Gong et al, 2023).

Research has examined differences and similarities in road safety conditions before, during, and after the COVID-19 pandemic using various methodologies, including models such as logit, mixed effects binomial, interrupted time series, binomial generalized linear, Chi-squared, and mixed negative (Adanu et al., 2022; Alsofayan et al., 2022; Alnawmasi and Mannering, 2023; Georgeades et al., 2023; Hasan et al., 2023; Kabush et al., 2023; Zhao et al., 2023). Additionally, evidence from spatial studies supported by geographically weighted Poisson and geographically weighted generalized linear models has been presented (Soltani et al., 2023; Soltani et al., 2023). In the epidemiological context of traffic-related injuries, no precedents were found for the use of random walk to complement the spatial analysis of the distribution of events of interest within the framework of an extraordinary event such as the COVID-19 pandemic.

Based on the previous considerations, the purpose of this research is to predict the behavior of the mortality frequency of the most vulnerable road users in three moments: before, during, and after the confinement caused by COVID-19 in Santiago de Cali, Colombia. To carry out this purpose, the research consists of four stages which analyze the data provided by the Cali Sustainable Mobility and Road Safety Observatory (OMSSVC) as follows: (i) delimit the study area and collect data on road crashes in Santiago de Cali, (ii) statistical analysis, (iii) geographical analysis (Kernel density maps) and (iv) predictions within the framework of the probabilistic random walk considering the physics and mathematics of the dynamic behavior of the most vulnerable road users in all three moments. The research emerges due to the lack of action plans in urban transportation that contribute to road safety and reduce contagion in times of pandemic.

The random walk technique is essential for modeling traffic accidents during the COVID-19 pandemic due to its ability to address uncertainty in mobility caused by movement restrictions and traffic flow variations that directly affect the probability of accidents. Understanding this probability is crucial for competent authorities to implement preventive measures, such as speed limits and educational campaigns, as well as to more efficiently allocate emergency resources, such as caring for accident victims during new outbreaks of the pandemic or other similar events.

2. Review of literature

Several studies have been carried out that have taken as a reference point the confinement measures adopted during the COVID-19 pandemic to evaluate their impact on road safety. Research was developed to evaluate the impact of COVID-19 on both the frequency and severity of injuries before and after the pandemic, and it was found that the severity of crashes increased due to non-use of seat belts and the increase in the speed of circulation of different transport modes, and that the impact of the pandemic changed during its different stages, making it necessary to evaluate its impact using local data (Gong et al., 2023).

Higher speed during the pandemic is considered one of the possible consequences of the decrease in traffic volume during the year 2020 compared to the average volume observed in previous and subsequent years. The consequences of an increase in speed value can be reflected in the type of road crash and reactions related to higher speed such as sudden accelerations and braking (Islam et al., 2022), thus increasing the severity of the crash (Adanu et al., 2021; Gong et al., 2023; Shaik and Ahmed, 2022). However, the relationship between the speed impact of the road crashes shows different results, one of the possible reasons why this relationship does not occur is due to the observation window selected for the study, which may vary between the different stages of the pandemic (Islam et al., 2022; Gong et al., 2023).

Confinement measures increased the use of bicycles because it is an individual transport mode (Shaik and Ahmed, 2022). In research carried out in New York, the authors found that the frequency of deaths and injuries among cyclists doubled when a comparison was made with the results of previous years (Li and Zhao, 2022). An external factor that can contribute to crashes is found in road infrastructure. By conducting a systematic review on risk factors related to road infrastructure, they found that traffic volume and composition, inadequate friction on the road surface, poor visibility, and adverse weather, are among the most impactful risks (Papadimitriou et al., 2019).

In the national context, over the last decade an average of more than 60 thousand motorcycles have been registered at the Valle del Cauca state including its capital, Santiago de Cali, which represents 2.6 times more than the average number of automobiles registered per year. In the city, by the year 2020, around 300 people died due to traffic events, 60% of pedestrians were hit by a motorcycle, and 32.9% of the deceased motorcyclists collided with a fixed object (Ospina et al., 2021). The global status report on road safety shows that pedestrians and cyclists accounted for 26% of all deaths, while 28% are among motorcyclists (WHO, 2018). To address this problem, the research conducted analyzes all the critical risk factors for the occurrence of crashes and the severity of injuries in crashes related to motorcycles (Wang, 2022).

From the perspective of transportation engineering, the relationship between crashes and road infrastructure has been studied through the execution of different projects so that the competent authorities can propose measures that help mitigate this phenomenon in the cities. Before the pandemic, an investigation was carried out in Santiago de Cali that characterized pedestrian crashes through the georeferencing of records and the generation of density maps at the neighborhood level and identifying the areas with the highest number of pedestrian crashes in the city, which have a significant relationship with some of the factors of the city's road infrastructure, since this phenomenon was represented at 0.7% (Garzón, 2019). However, these relationships must be explored in greater depth based on more variables. Regarding the evaluation of the interventions carried out in the infrastructure in order to reinforce road safety, projects developed in Santiago de Cali stand out to evaluate the impact of the installation of photo detection cameras (Martínez et al., 2019), the segregation of one lane for motorcycles (Osorio et al., 2017) and the relationship between investments in transportation infrastructure and the urban structure of the city with the distribution of deaths due to road crashes (Vivas et al., 2023).

The analysis of the historical behavior of the number of fatalities due to road crashes has become increasingly relevant, since it constitutes a public health problem (WHO, 2014; WHO, 2018), so reducing the number of road crashes is one of the initiatives of the United Nations (2017). In this way, several analytical models have emerged (Fawcett et al., 2017; Gu et al., 2016) to provide solutions to this problem that allow establishing preventive measures (Salas et al., 2019). Although these models are useful, the difficulty of globally proposing a single analysis model still prevails (Gutiérrez and Pedraza, 2020; Jomnonkwao et al., 2020), since different variables that are incorporated into these models depend on the study area and are generated from a causal perspective.

In this sense, predicting the behavior of road crashes has not been a simple topic to establish based on statistical studies. To predict these cases, the establishment of the causes of fatalities in real time, in the medium, short, and long term has been considered (Antoniou et al., 2016; Zhang et al., 2018; Zhao et al., 2019). In a study carried out for the prediction of crashes in real time using a bayesian network, it is highlighted that the variables considered in the prediction models are highly correlated due to the nature of the phenomenon, for this reason, the modeling methods used must be sufficiently robust to adjust these variables. Other real-time predictions have encountered difficulties in their predictive model due to the computational delays generated by the transmission of data, increasing the complexity of the algorithm and therefore of the predictions (Zhao et al., 2019).

On the other hand, from the context of a methodology based on probabilistic random walk, it has been possible to make annual predictions of the number of injuries or fatalities due to traffic crashes. The methodology consists in the solution of a second-degree equation developed from the context of a probabilistic random walk. The predictions of the number of fatalities due to road crashes achieved a success rate of 97.3% when compared to the number of fatalities reported for the year 2014 in the state of Florida—USA (Rodríguez et al., 2019a). Regarding the number of injuries due to road crashes in the municipality of Ibagué (Colombia), for the year 2010, a success rate of 90.2% was achieved (Rodríguez et al., 2019b); and for the year 2010 in Colombia the prediction achieved a correct percentage of 86.6% (Rodríguez et al., 2020).

3. Methodology

This section describes the research process, which consists of four stages: i) delimiting the study area and collecting data on road crashes in Santiago de Cali; ii) statistical analysis; iii) geographic analysis (maps of Kernel density) and iv) physico-mathematical prediction of the behavior of the frequency of road crash frequency in Santiago de Cali before, during and, after the COVID-19 pandemic (see **Figure 1**).

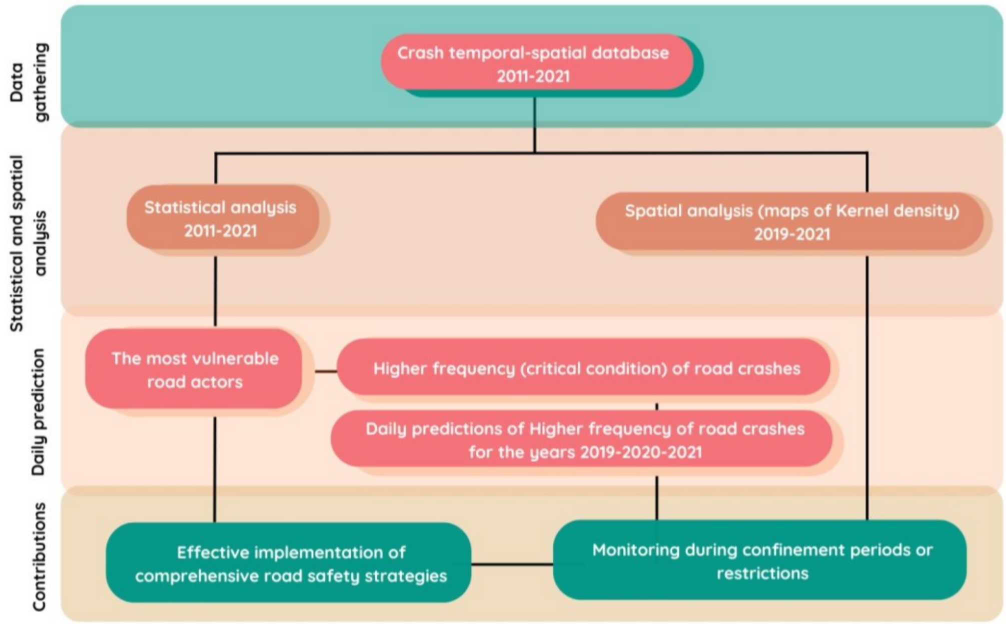


Figure 1. Research process before, during and after COVID-19.

3.1. Study area

The study area in this research is the city of Santiago de Cali located in Colombia in the Valle del Cauca state; it limits to the north with the municipalities of La Cumbre and Yumbo, to the south with the municipality of Jamundí, to the west with the municipalities of Buenaventura and Dagua, and to the east with the municipalities of Palmira, Candelaria, and Puerto Tejada. This can be seen in **Figure 2**. It has a total area of 560.3 km^2, of which 120.9 km^2 corresponds to urban areas divided into administrative districts called communes and 439.4 km^2 corresponds to rural areas. The city is organized into 22 communes in the urban area and 15 townships in the rural area. For the year 2020, the population of Cali according to the National Administrative Department of Statistics was 2,252,616 inhabitants, with 46.7% men and 53.3% women. The population by area of residence is estimated to be 97.9% living in the urban area and the remaining 2.1% in the rural area (Holguín et al., 2020). Regarding the vehicle fleet, for the year 2020, around 460,000 vehicles, 225,000 motorcycles, 25,000 taxis, 18,000 cargo vehicles, 15,000 buses and 10,000 other types of vehicles were registered. Finally, regarding the public transportation services, by 2022, 2.2% of the vehicle fleet in service corresponded to the bus mass transport system, mobilizing approximately 2.5% of passengers transported (DANE, 2022).

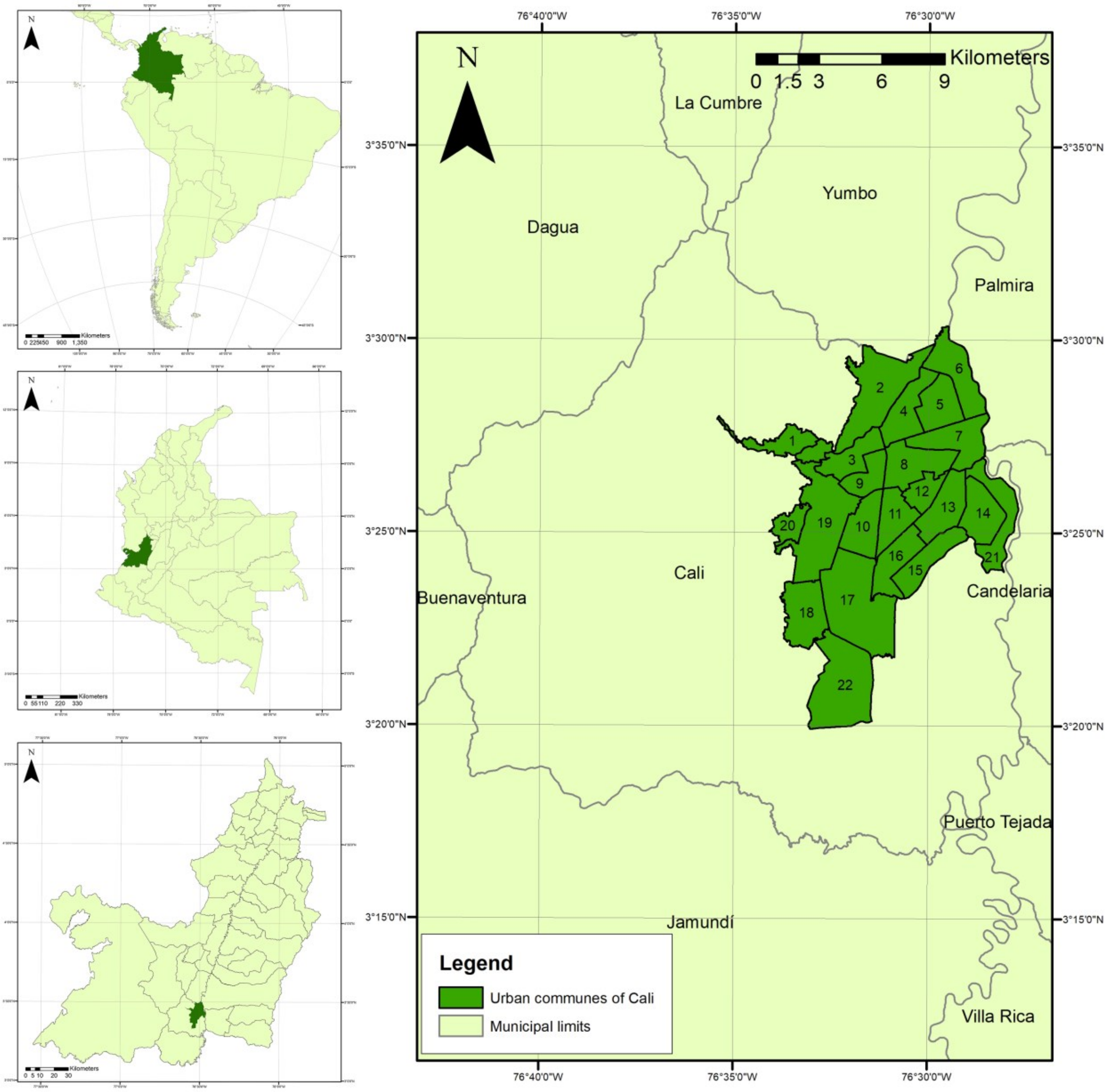


Figure 2. Location of the study area.

3.2. Data source

The annual reports (2011 to 2021) registered in the database of the Cali Observatory of Sustainable Mobility and Road Safety (OMSSVC) of Santiago de Cali and provided for this study were systematized in an Excel® spreadsheet. An analysis of the data was carried out considering the following available variables: day of the week, age group, and condition of the deceased for which the categories were defined as 0–20 years, 21–30 years, 31–40 years, 41–50 years, 51–60 years, >60 years (age group); cyclist, driver, motorcyclist, motorcycle passenger (M + P), car passenger, pedestrian, no information (condition of the deceased).

3.3. Descriptive analysis

A multi-year descriptive statistical analysis was carried out to recognize possible relationships between the variables that showed relevance in the behavior of road crashes before, during, and after the COVID-19 pandemic. The analysis was carried out between the years 2011–2021, initially revealing the behavior in the frequencies of traffic crashes considering the daily records of traffic crashes from the entire years 2011 to 2021, with a sample size of 3259 records; thus, obtaining the frequencies of specific categories of the variables that presented peaks or valleys in the observation window and that had the highest frequency. For the objective of the research, which is the study before, during and after the pandemic, an observation window was defined that considers the entire years 2019, 2020, and 2021, with sample sizes of 309, 300 and 294 records, respectively.

3.4. Spatial analysis

The database provided by the OMSSVC was georeferenced by carried out with the purpose of spatially analyzing road crashes using Kernel density in the years 2019 to 2021 (pre, during, and post pandemic periods). For this, the ArcGIS® software was used, where the calculation was carried out considering planar distances between the points, a search radius calculated by the software, using a spatial variant of Silverman's general rule that is resistant to spatial outliers, which are, points that are far from the rest of the points and a cell size equally calculated by the software. In addition, once this variable was calculated, 9 categories were defined for its visual representation, with the same extreme values, to carry out the corresponding analysis.

3.5. Daily prediction of road crash frequency

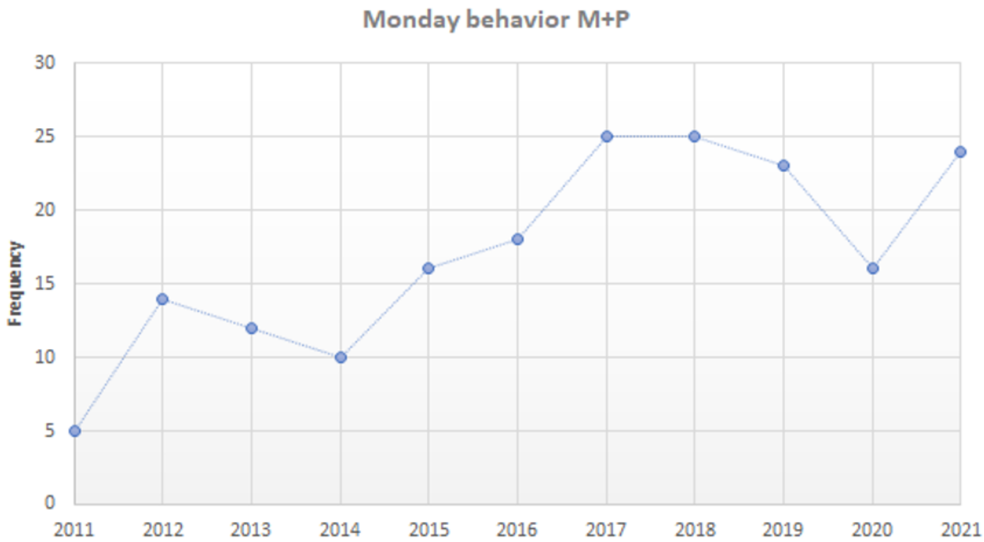
From the condition that presented a higher frequency (critical condition) of road crashes, daily predictions of its behavior were made, considering three-time windows, the first between the years 2011 to 2018 to predict the behavior in 2019 (see **Figure 3**), the second between the years 2011 to 2019, to predict the behavior in 2020, and the third one between the years 2011 and 2020, to predict the behavior of 2021. By generating the graph of the daily crash frequency for the three observation windows, the length could be calculated that separates two ordered pairs, for this the points $[(X_o, Y_o), (X_1, Y_1)]$, $[(X_1, Y_1), (X_2, Y_2)]$, $[(X_2, Y_2), (X_3, Y_3)]$, ... $[(X_{n-1}, Y_{n-1}), (X_n, Y_n)]$ where *n* is the number of data to be analyzed and its equation is the following:

$$L = \sqrt{\left(X_f - X_o\right)^2 + \left(Y_f - Y_o\right)^2} \tag{1}$$

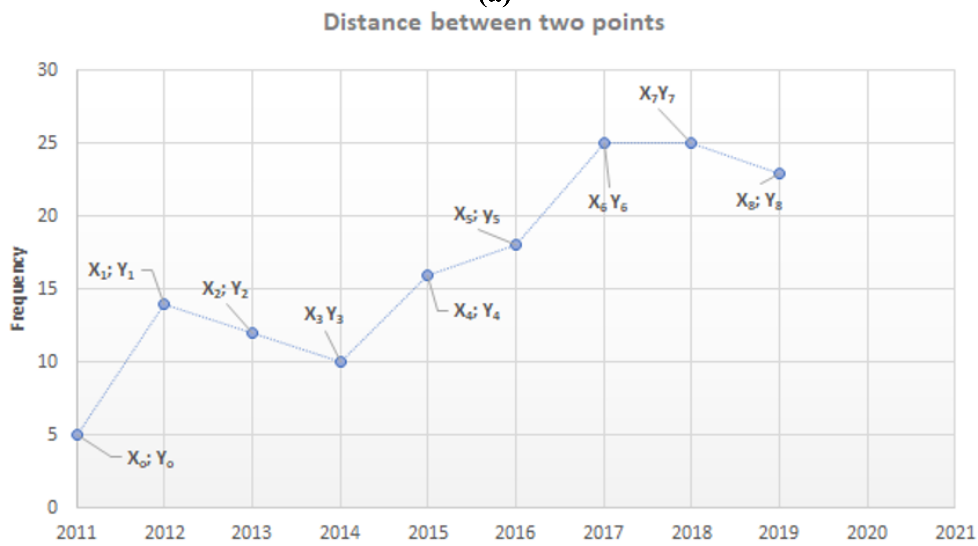
where the X coordinate is the year, and the Y coordinate is the daily crash frequency for a given road user. After evaluating the length with Equation (1), its probability was calculated with the following equation:

$$P(L) = \frac{\text{Length of the daily frequency of crashes}}{\text{Total of lengths}} = \frac{L}{TL} \tag{2}$$

It should be noted that the probability of Equation (2) differs from the calculation of the probability that could evaluate the frequency of daily road accidents in a given year, where Equation (2) evaluates the geometric variations of the days of the week year to year, on the total sum of all these geometric variations, while in the other probability the frequency of annual daily road crashes is evaluated with according to the sum of each of them.



(a)



(b)

Figure 3. Representation of the behavior. **(a)** the random dynamics of Monday for M + P; **(b)** the ordered pairs of this dynamic.

Once the calculations were carried out with Equations (1) and (2) for the three observation windows, the values of the last three lengths and their probabilities found with these two equations were selected, to then add these three lengths (TL) and calculate the arithmetic average of their probabilities $P(L)$, to later substitute each of these values into the following equation:

$$Y_o = \frac{2Y_{f} \pm \sqrt{\left(-2Y_f\right) - 4\left\{Y_f + (X_f - X_o)^2 - \left[P(L)^2 \times (TL)^2\right]\right\}}}{2} \tag{3}$$

By carrying out the respective algebraic development between Equations (1) and (2), the Equation (3) was reached, where the term Y_f corresponds to the daily crash frequency that is found before the frequency of these to be predicted. When carrying out the respective algebraic development indicated in Equation (3), two results are obtained from which it is necessary to establish a single value through an analysis of the behavior of two possible events, called Increases “I” and Decreases “D”. For this, the frequency of appearance of the number of "I" and "D" was calculated during the period between the years 2011 to 2019 and subsequently its probability. If event "D" has a higher probability, the average value of the two solutions returned by Equation (3), and the result is added with the minimum value returned by Equation (3), now, if the event with the highest probability is "I", the calculated average value is added with the maximum value given by Equation (3). This result is averaged again, thus obtaining a single value for the year 2019.

Subsequently, the probability of event "I" or "D" and the two solutions found were analyzed jointly with Equation (3), which are understood in this methodology as a range delimited by a maximum and a minimum that allows theoretically establishing where the crash frequency of a group of road users can vary. All the previous steps were carried out to make the daily prediction of the crash frequency of a certain road user for the years 2020 and 2021.

Finally, the percentage of correct predictions was calculated using a simple rule of three between the crash frequency found from the OMSSVC data and the predicted value. If the predicted value is greater than the crash frequency found from the OMSSVC data, the simple rule of three is applied in the same way and the result is interpreted as how close the predicted value is to the actual value.

4. Results and discussion

By identifying the most vulnerable road users among three key moments of the confinement caused by COVID-19 in Santiago de Cali, the way in which the results respond to the objective set in the research is described below.

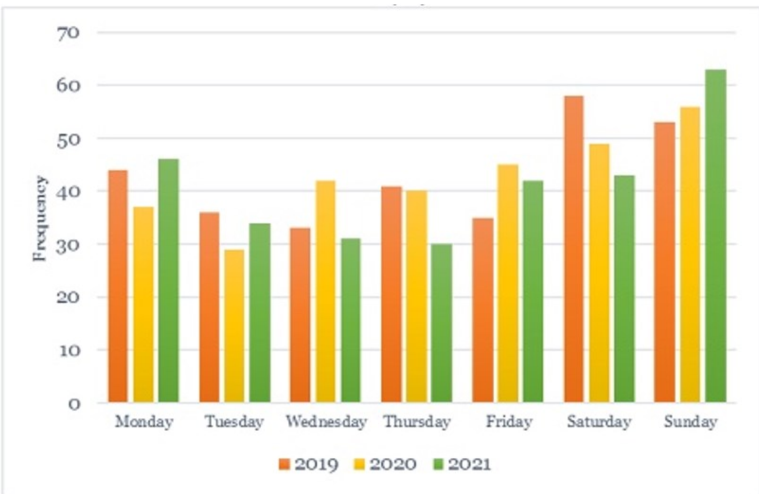
4.1. Statistical analysis

Table 1 shows statistics of the daily records for the variables day of the week, road user condition, and age group, for the years 2019, 2020 and 2021, considering the medians for the categories of each variable by year, that is, the median of the individual values for each day of the week, and their percentage variations compared to the previous year. Also, the minimum and maximum values are observed, and the variation of the maximum value compared to the previous year.

Table 1. Behavior of road crashes, period 2019–2021, by day of the week, condition of the deceased, and age group.

Variable	Year	Median	Median variation (%)	Min	Max	Max variation (%)
Day of the week	2019	41	-	33	58	-
	2020	42	2%	29	56	−3%
	2021	42	0%	30	63	13%
Condition	2019	36	-	2	131	-
	2020	41	14%	4	140	7%
	2021	25	−39%	5	141	1%
Age group	2019	39	-	26	103	-
	2020	36	−8%	30	91	−12%
	2021	39	8%	33	80	−12%

In these data, a high variability can be observed in the median of the road user condition variable, with variation values of 14% and 39% for the years 2020 and 2021, respectively, compared to the other two variables, which have a variation of the median below 10%.



(a)

(b)

(c)

Figure 4. Representation of the behavior of the variables for the time series from 2019 to 2021. **(a)** day of the week; **(b)** road user deceased; **(c)** age group.

Figure 4 shows the behavior of the three variables with their respective categories for the three years considered. Part (a) refers to the variable day of the week, in which a peak of deaths recorded is observed during the weekend associated with driving during the night and under alcohol effects which contribute to crash risk (Keall et al., 2005), while on Mondays and Tuesdays there was a valley for the year 2020, compared to the same days in the pre- and post-pandemic years. The observed peaks and valleys during the pandemic provided key information that allowed to establish differences between the behavior of the mortality frequency before and after the containment measures, as well as in road safety issues to implement preventive measures and safety controls at different time slots. Part (b) refers to the variable road user condition of the deceased, where a peak of deaths recorded for cyclists is observed, while the condition of pedestrian showed a valley for the year 2020, compared to the same condition before and after the pandemic; in addition, it can be observed that the most frequent categories were motorcyclists plus motorcycle passenger (M + P) and pedestrians, while the ones with the least frequency were driver and car passenger those results are related to motorcycles speeding and unsafe lane change (Ospina et al., 2021). Part (c) refers to the variable age group of the deceased, where a peak of deaths registered is observed for the group from 21 to 30 years old, while the group from 31 to 40 years old presented a valley for the year 2020, compared to the same condition in the pre- and post-pandemic years. Regarding age, the group close to 30 years old is the one that contributes the most, as reported in the bibliography (Feleke et al., 2018, Regev et al., 2018), this may be associated with a greater exposure caused by work related activity.

After observing the behavior of the variables, an individual analysis was carried out for the road user conditions of motorcyclist plus motorcycle passenger, pedestrian, and cyclist. **Table 2** shows the variation in frequency compared to the previous year, its percentage variation and whether the behavior was an increase (I) or decrease (D). It should be noted that in all categories there was a peak or valley for the year 2020, except for the category of motorcyclist and motorcycle passenger, which had an increase for the years 2020 and 2021.

Table 2. Behavior of road crashes, period 2019–2021, by road user.

Category	Year	Total	Variation	Variation (%)	Behavior
	2019	129	-	-	-
M + P	2020	140	11	9%	Increase
	2021	141	1	1%	Increase
	2019	131	-	-	-
Pedestrian	2020	105	−26	−20%	Decrease
	2021	112	7	7%	Increase
	2019	36	-	-	-
Cyclist	2020	41	5	14%	Increase
	2021	25	−16	−39%	Decrease

Table 3 shows the frequencies in relation to the two remaining variables, which are, the frequencies of each category by day of the week and by age group; in addition,

the same descriptive statistics indicators that were obtained for the initial variables: median of all categories, variation of the median, minimum, maximum and variation of the maximum. This highlights the high variability of the categories with respect to the variables, where only the relationship between M + P and Pedestrians with age group between the years 2019 and 2020 had a median variation below 20%.

Table 3. Behavior of road crashes, period 2019–2021, for each of the categories studied, in relation to other variables.

Category	Related variable	Year	Median	Median variation (%)	Min	Max	Max variation (%)
M + P	Day of the week	2019	14	-	9	27	-
		2020	17	21%	13	33	22%
		2021	17	0%	12	36	9%
	Age group	2019	15	-	9	57	-
		2020	16	7%	12	59	4%
		2021	21	31%	7	49	−17%
Pedestrian	Day of the week	2019	18	-	11	26	-
		2020	13	-28%	8	23	−12%
		2021	17	31%	12	19	−17%
	Age group	2019	12	-	2	78	-
		2020	11	−4%	3	59	−24%
		2021	14	23%	2	58	−2%
Cyclist	Day of the week	2019	5	-	3	8	-
		2020	6	20%	4	7	−13%
		2021	3	−50%	1	6	−14%
	Age group	2019	5	-	2	15	-
		2020	7	44%	1	14	−7%
		2021	3	−54%	0	11	−21%

Figure 5 shows the behavior of the categories in comparison with the two remaining variables. The first row shows the behavior of the categories with respect to the variable day of the week, and the second row shows the behavior with respect to the age group, using the same scale on the frequency axis for each comparison. In these graphs it can be seen, for the day of the week variable, the road user of M + P showed the maximum value of 36 crashes for Sunday in the year 2021, while the age group variable, the road user condition of pedestrian showed the maximum value of 78 crashes for the age group of people over 60 years in 2019. In addition to this, different peaks can be observed: for the road user M + P, there was a peak on Tuesdays, Wednesdays, Thursdays and Saturday, and in the age group of 21–30 years and over 60 years; for pedestrians there was a peak on Friday; for road user cyclists there were peaks on Monday, Tuesday, Thursday, Friday and Sunday, as well as for the age groups of 0–20 years and 51–60 years. In the same way, valleys were present: For the road user M + P there were valleys on Mondays and Fridays, and in the age group of 0–20 years; for pedestrians there were valleys on Tuesday and Sunday, and in the age groups of 31–40 years, 41–50 years, and 51–60 years. For cyclists there was only a valley on Saturday. This situation is estimated to be associated with the growing trend

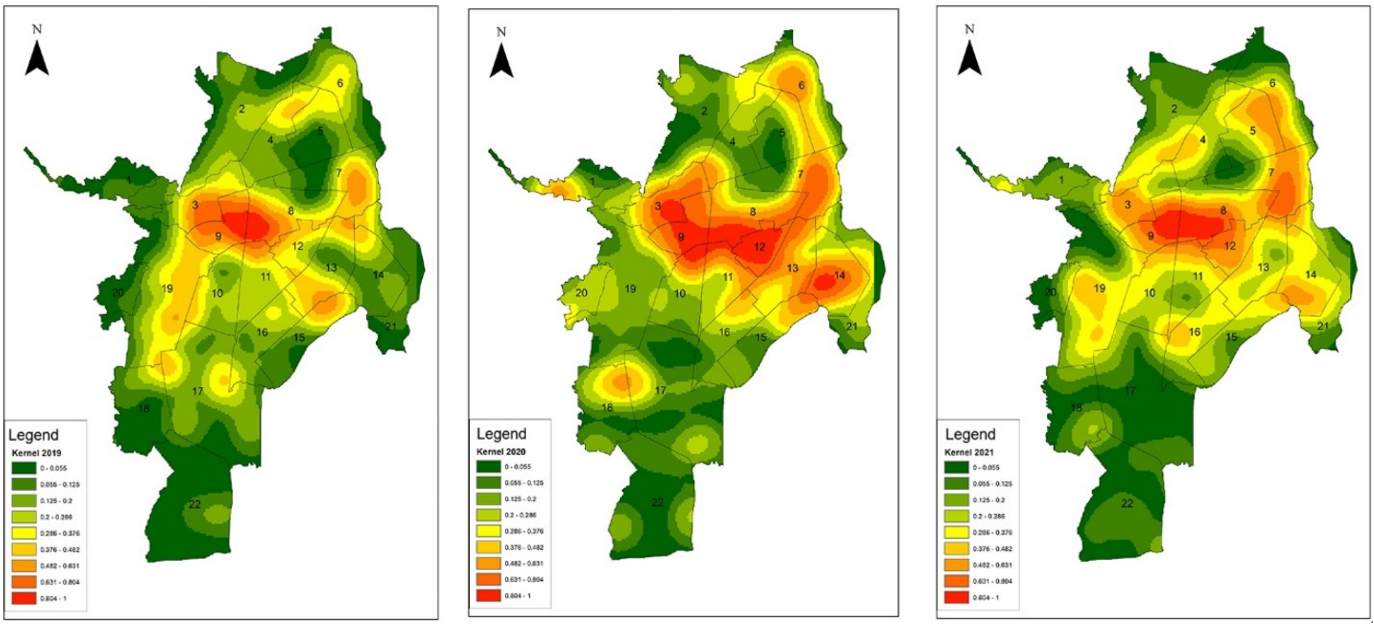
of motorcycle use (Montero, 2018), the high proportion of walking in the modal split and the deficient infrastructure for bicycles in various territorial areas, aspects similar reported by other authors (Fernandes and Boing, 2019; Feleke et al., 2018; Nantulva and Reich, 2003; Prati et al., 2018).

Figure 5. Representation of the behavior of the categories analyzed for the time series from 2019 to 2021, in relation to other variables. **(a)** motorcyclist plus motorcycle passenger by day of the week; **(b)** pedestrian by day of the week; **(c)** cyclist by day of the week; **(d)** motorcyclist plus motorcycle passenger by age group; **(e)** pedestrian by age group; **(f)** cyclist by age group.

4.2. Spatial representation results

Once the spatial distribution was obtained for the years before, during, and after the pandemic, the Kernel density was found. For the year 2019, a large concentration could be observed in the central area of the city, with a small concentration in the eastern area. In 2020, despite maintaining the concentration in the central area of the city, there were outbreaks in communes 1, 6, 14, 18 and 20, located on the outskirts of the city. By 2021, there was once again a greater concentration in the city center, with a small focus in the same peripheral communes as in 2020. This is a typical pattern for a monocentric city like Santiago de Cali in which most business activity, and the trade of goods and services are located around downtown, having residents commuting daily with high frequency to this part of the city.

When the years 2019 and 2020 were contrasted, an increase was initially noted in the peripheral communes mentioned for the year 2020, which are from a low average socioeconomic level; however, a decrease in crashes could also be observed in the area where health services are offered in commune 19, which is one of the areas with the highest concentration of health-providing institutes (IPS), private clinics and public hospitals in the city (CEDETES—Universidad del Valle, 2007). Comparing the years 2020 and 2021, a slight decrease was observed in the peripheral communes, which showed an increase in year 2020, as well as a slight increase in the concentration of crashes in the area where health services are offered in commune 19. Between the years 2019 and 2021, a similar concentration was observed in the central area of the city, however, an increase in crashes was also noted in peripheral areas, especially in the eastern part of the city. All these changes and density distribution can be observed in **Figure 6**.



(a) **(b)** **(c)**

Figure 6. Spatial distribution of road traffic crashes in the city of Santiago in Cali. **(a)** year 2019; **(b)** year 2020; **(c)** year 2021.

4.3. Probabilistic random walk

According to the previous results, the frequency of daily mortality for road users of motorcyclist plus motorcycle passenger (M + P), which were considered as a single road user condition in this research, varied between 9 and 27 for 2019, between 13 and 33 for 2020. Between 12 and 36 between 2021. For pedestrians it varied between 11 and 26 for 2019, between 8 and 23 for 2020, between 12 and 19 for 2021. For cyclists it varied between 3 and 9 for 2019, between 4 and 7 for 2020, between 1 and 6 for 2021 (see **Table 4**).

Table 4. Mortality frequency of the number of crashes in bicycle, motorcycle, and motorcycle passenger road users, by day of the week and the predicted value for the years 2019, 2020 and 2021 in the District of Santiago de Cali.

Day		2019						2020						2021					
		F*	S1¤	S2¤	P£	E±	%	F	S1	S2	P	E	%	F	S1	S2	P	E	%
	Monday	23	30	20	28	I	82	16	27	19	25	I	64	24	33	13	28	I	86
	Tuesday	13	19	7	16	I	81	14	19	7	16	I	88	12	19	9	17	I	71
	Wednesday	14	27	13	23	I	61	20	20	8	17	I	85	16	26	14	23	I	70
M + P	Thursday	9	21	15	19	D	47	17	21	15	17	D	100	14	24	10	13	D	93
	Friday	14	31	13	27	I	52	13	21	7	17	I	76	20	17	9	15	I	75
	Saturday	25	29	13	25	I	100	27	34	16	29	I	93	17	32	22	30	I	57
	Sunday	27	32	24	30	D	90	33	29	25	26	D	79	36	36	30	32	D	89
	Monday	11	31	23	29	I	38	13	20	2	15	I	87	17	21	5	17	I	100
	Tuesday	18	27	21	25	I	72	8	22	14	20	I	40	15	15	1	12	I	80
	Wednesday	11	26	16	24	I	46	13	17	5	14	I	93	12	19	7	16	I	75
Pedestrian	Thursday	26	32	18	29	I	90	17	31	21	29	I	59	13	23	11	20	I	65
	Friday	16	30	18	27	I	59	23	23	9	20	I	87	19	31	15	27	I	70
	Saturday	22	34	16	30	I	73	17	29	15	26	I	65	17	22	12	19	D	89
	Sunday	22	23	19	22	I	100	13	23	21	23	I	57	18	17	9	15	I	83
	Monday	5	6	4	6	I	83	7	6	4	5	D	71	3	8	6	6	D	50
	Tuesday	6	4	0	3	I	60	6	9	3	7	I	86	5	9	3	7	I	71
	Wednesday	9	8	1	7	I	88	6	10	6	9	I	67	1	9	3	7	I	14
Cyclist	Thursday	4	4	2	2	D	50	5	5	3	5	I	100	2	6	4	6	I	33
	Friday	5	6	0	5	I	100	6	8	2	7	I	86	3	9	3	7	I	43
	Saturday	6	11	5	7	D	86	4	9	3	5	D	80	6	6	2	3	D	50
	Sunday	3	8	−4	-	-	-	7	7	−1	-	-	-	5	11	3	9	I	56

F*: Frequency; S1¤ and S2¤: solution 1 and solution 2; P£: prediction, E±: event and %: percentage of the prediction.

The daily prediction for road users of M + P varied between 16 and 30 for 2019; between 16 and 29 for 2020; between 13 and 32 for 2021. A comparison between the predicted values greater than the crash frequency values found from the OMSSVC data shows that they were not double these values. The percentage of accuracy of the predictions and the road crash frequency found with the OMSSVC data for 2019 varied between 47% and 100%; between 64% and 100% for 2020; between 57% and 93% for 2021. The crash frequency on Thursday for the year 2019 was found outside the theoretical range; while for 2020 it was Wednesday and for 2021 it was Friday and

Saturday (see **Table 4**).

The daily prediction for pedestrians varied between 8 and 22 for 2019; between 14 and 29 for 2020; between 8 and 12 for 2021. A comparison between the predicted values that were greater than the actual values shows that none were double these values. The percentage of success of the predictions for the seven days of the week and the actual values for 2019 varied between 38% and 100%; between 40% and 93% for 2020; between 65% and 100% for 2021. The crash frequencies that were found outside the theoretical range for the year 2019 were Mondays, Tuesdays, Wednesdays, and Thursdays; for 2020 were Tuesday, Thursday, and Sunday, while none of the seven days of the week in 2021 were outside this theoretical range (see **Table 4**).

The daily prediction for cyclists varied between 7 and 2 for 2019; between 9 and 5 for 2020; and between 9 and 3 for 2021. When comparing the predicted values and the actual values, it was found that for 2019 the predictions for Monday and Saturday were greater than the actual value; for the other days the predictions were below this value. For the year 2020, the six days on which it was possible to make the prediction did not exceed double the real value. For 2021, on Monday, Wednesday, and Thursday, the predictions were below the real value, the other days they were above the real value. The percentage of success of the predictions and the actual value for 2019 varied between 50% and 100%; between 67% and 100% for 2020; between 50% and 71% for 2021. The crash frequency on Thursday for the year 2019 was found outside the theoretical range; While for the year 2020 it was Wednesday, and for the year 2021 it was Friday and Saturday (see **Table 4**).

The set of prediction results for the three most vulnerable road users showed that during the containment measures not only did the behavior of the mortality frequency changed for the road users in pre and post pandemic, but also the days in which an underreporting in the reports could occur. For example, it was observed that for the year 2021 the daily mortality frequency for pedestrians was within the theoretical ranges, while during the pandemic on Tuesday, Thursday, and Saturday these frequencies were slightly lower than predicted. The previous analysis can be carried out for M + P and cyclists, which draws attention to Saturday for cyclists where it was not possible to make predictions before and during the pandemic for this day, but it was possible after the pandemic. Because of all the above, the predictions also highlighted behaviors that are intrinsic to the mortality cases, providing more elements of analysis for the road safety plans in Santiago de Cali, where it is proposed to reinforce prevention measures for the three road users. Likewise, establish new monitoring systems for every day of the week.

According to the previous results, the statistical analysis of the frequency of mortality due to road crashes helped to define and characterize the three most vulnerable road users in Santiago de Cali in the pre and post pandemic times to make daily predictions of the behavior of each road user. Additionally, it was possible to describe the behavior and triggering relationships of other crash variables during the pandemic. To do this, road user condition and age group were analyzed, which had very different behavior within their categories. This means that the differences between the categories of the road user condition were very high, with the conditions of car driver and car passenger having much lower frequencies than the conditions of motorcyclist with M + P, pedestrian, and cyclist; to put it in perspective, in the 3 years analyzed, a total of 11 drivers and 410 motorcyclists and motorcycle passengers died, a 3.7% increase. Something similar occurred in the analysis by age group, where the critical categories were the groups of 21–30 years and >60 years, with a total of 274 people died for this last group in the three years analyzed, while for the group from 0 to 20 years old there were a total of 89 deaths, 67% less.

The critical categories for the road user condition variable were motorcyclist with motorcycle passenger, pedestrian, and cyclist, which showed great variability when analyzed by age group. In the M + P condition, for the age group over 60 years of age there were a total of 28 deaths in the three years analyzed, while for the age group of 21–30 years there were 165 deaths (58.9% more). In the pedestrian condition, for the age group of 0–20 years there were a total of 7 deaths in the three years analyzed, while the age group of over 60 years had 195 deaths (27.9% more). Finally, for the cyclist condition, the age group of 41–50 years old had a total of 5 deaths in the 3 years analyzed, while for the age group over 60 years old, there were 40 deaths (80% more).

It should be noted that these analyzes were carried out considering only the categories with the highest and lowest total frequency, but they served to reveal the high variability within the categories of the variables, expressed in the variation values initially calculated. In the same way, it is important to highlight that the maximum and minimum values of these categories were not presented for the same age groups, for example, for motorcyclists and M + P the age group of 21 to 30 years was the one with the highest frequency, while for pedestrians, it was the age group over 60 years of age, which, in turn, is the age group with the lowest frequency for motorcyclists and M + P. This varies greatly according to the dynamics and compositions of each road user, for example, it is known that the motorcycle is the vehicle most used by low-income young people in Santiago de Cali, and the risky behavior of road users makes it become a transport mode with a high crash rate for this age group (Ospina et al., 2021). Considering the increase in traffic speed during the pandemic, due to the decrease in vehicle volume on the roads, added to the way in which young people drive motorcycles, the peak in deaths for this age group can be explained by this road user condition.

Just as young people engage in risky behavior when using motorcycles as a transport mode (Wang, 2022), elderly, especially those over 60 years of age, have characteristics that make them more vulnerable in the case of a traffic crash; due to their motor, cognitive, perceptual, and visual deficiencies, they have impairments in their reaction abilities, in addition to being three and a half times more likely to be fatal victims than a young person (Agencia Nacional de Seguridad Vial, 2022).

The results of the spatial representation are relevant in this research because they allowed to observe the concentration of fatal crashes in the peripheral communes of Santiago de Cali in the context of the pandemic, which have a low average socioeconomic level. This can be explained by the increase in traffic speed and the risky behaviors already discussed. For the year 2021, although the concentration in these areas decreased, they did not reach the levels of 2019, and this is why the analysis of Kernel density is a tool with which recommendations can be made related to the controls of the road regulations in these communes in which the concentration of crashes increased, which are 1, 6, 14, 18 and 20. The low average socioeconomic level in these communes is discussed, since in other peripheral communes, such as the 22 or 17, showed a much lower concentration than those initially mentioned, and these two mentioned communes have a high average socioeconomic level, which gives indications for future studies that relate crashes to socioeconomic level.

To have a clearer idea from which perspective the predictions were made from, it is necessary to consider that the daily behavior of road accidents is stochastic; this behavior is characterized by the number of variables associated with crashes, which makes it difficult to establish a single statistical trend of one or several variables implicit in this behavior in the future. With this idea, a methodology was applied which makes an analogy between a random walk and the behavior of an epidemiological variable (Rodríguez et al., 2019a, 2019b, 2020), which in this case is the frequency of daily road crashes for the three temporary windows. It should be noted that the study of a model based on random walk requires, in most cases, an advanced mathematical formalism (Riascos et al., 2020). In this methodology, the degree of difficulty was reduced by analyzing the geometric behavior of the lengths of the day of the week and the probability for each of them. The predictions are established from the solution of a second degree equation considering how strong the probability is that there will be an increase or decrease in the frequency of road crashes for the day of the week analyzed.

In theoretical physics, the definition of the possible behavior of a dynamic variable causes it to become deterministic, and this is precisely what is achieved with the solution of the quadratic equation in the context of a probabilistic random walk. Another aspect to highlight in this methodology is found in the predictions, which are made based on the daily crash frequency previously calculated in the descriptive analysis. In this way, the randomness observed in the variables analyzed can be predicted in the context in which the methodology applied in this research was developed.

Given all the uncertainty that the pandemic triggered, predicting the behavior of the mortality frequency of the most vulnerable road user can contribute to road safety plans in Santiago de Cali. The predictions made were carried out with the daily crash frequency of the three years preceding the year to be predicted, which shortens the response time provided a clearer idea of the possible behavior of the crash frequency for a certain road user. For the cases in which it was not possible to make the predictions, it was due to the frequency of road crashes, which was the same for more than two consecutive years, which is understood as stability in its behavior and not a variation, which is what the methodology evaluates. The last can be observed in the predictions made for the frequency of crashes for the cyclist road user, where a negative solution was found for Sunday in the years 2019 and 2020. In mathematical terms it may be correct, but the solutions in the context that was being analyzed represent a road crash that did not occur. In the case in which the crash frequency values are very far from the predicted values, the theoretical range allows for considering the possible existence of under-recording in the cases notified to the main source of the data used. Also, it works as a range that delimits the possible crash frequencies for each day of the week.

There are three lessons that the pandemic left on issues related to road safety, the first is to recognize that each city of Colombia, in terms of road crashes issues, has its own dynamics, that an aspect that contributes to its differentiation is the geographical space in which the roads have been built, as has been documented in different investigations (Umair et al., 2022). The second is the decrease in vehicle volume in urban centers, which contributes negatively to road safety after observing how the increase in speed triggers an increase in the severity of the crashes (Soltani, 2023; Adanu et al., 2021; Gong et al., 2023; Shaik and Ahmed, 2022). The third is the recognition of variables that are not direct effects of the pandemic, such as driver inattention, which are divided into five subtypes (Salmon et al., 2019; Regan et al., 2022; Wundersitz, 2019).

5. Conclusion

The findings of this study, based on the statistical analysis and spatial representation of road crashes in Santiago de Cali during the pandemic, highlight the need to address road safety from an adaptive and strategic perspective. The identification of significant differences in the geographical distribution of crashes emphasizes the importance of designing differentiated strategies for specific areas, focusing regulation and control measures in areas with high crash rates, especially those that showed an increase during confinement periods. Besides, the high vulnerability of certain age groups and road user conditions suggests the implementation of segmented educational programs adapted to these populations. Likewise, constant data monitoring and interdisciplinary collaboration between policy makers, health organizations and communities are fundamental pillars for the development and effective implementation of comprehensive road safety strategies and implement preventive measures, such as speed limits and educational campaigns, as well as more efficiently allocation of emergency resources. These recommendations could not only improve the response to emergency situations such as the pandemic, but could also strengthen long-term road safety plans, promoting safer environments for all road users in the city.

Recognizing the limitations that would ideally be addressed in future studies, such as the lack of detailed information and the necessity to integrate additional dimensions related to the epidemiological triad considered for these types of events, is crucial. Despite these challenges, our findings hold significance in enhancing the understanding of fatal traffic events during the COVID-19 pandemic and could greatly aid in informing the planning and development of public policies on urban mobility in extraordinary circumstances.

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