

## Article

# A GIS-Based Spatiotemporal Modelling of Urban Traffic Accidents in Tabriz City during the COVID-19 Pandemic

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**Abstract:** The main aim of the present study was to investigate the spatiotemporal trends of urban traffic accident hotspots during the COVID-19 pandemic. The severity index was used to determine high-risk areas, and the kernel density estimation method was used to identify risk of traffic accident hotspots. Accident data for the time period of April 2018 to November 2020 were obtained from the traffic police of Tabriz (Iran) and analyzed using GIS spatial and network analysis procedures. To evaluate the impacts of COVID-19, we used the seasonal variation in car accidents to analyze the change in the total number of urban traffic accidents. Eventually, the sustainability of urban transport was analyzed based on the demographic and land use data to identify the areas with a high number of accidents and its respective impacts for the local residences. Based on the results, the lockdown measures in response to the pandemic have led to significant reductions in road traffic accidents. From the perspective of urban planning, the spatiotemporal urban traffic accident analysis indicated that areas with high numbers of elderly people and children were most affected by car accidents. As we identified the hotspots of urban traffic accidents and evaluated their spatiotemporal correlation with land use and demography characteristics, we conclude that the results of this study can be used by urban managers and support decision making to improve the situation, so that fewer accidents will happen in the future.

**Keywords:** urban road; traffic accidents; hotspots mapping; GIS spatial and network analysis



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## 1. Introduction

Road safety is of particular importance because it plays a pivotal role in achieving sustainable transportation development [1]. Pedestrian and driver deaths and injuries due to road traffic accidents considerably affect society and can lead to substantial burdens on the national economy and healthcare system [2]. Therefore, it is necessary to investigate various aspects of traffic accidents in different geographic regions [3–5]. In this context, urban sustainable transportation aims to address the development of urban transport networks for supporting effective and safe mobility in urban environments. In fact, the sustainable transport sector is heavily influenced by social, economic, regulatory and technological factors. It is also tightly linked to other sectors of the economy and complements other operations related to neighboring countries' transportation industries [6].

Urban traffic accidents may be a significant issue in terms of pecuniary and non-pecuniary damage in urban environments that lead to loss of lives, personal injury, and lost

productivity [7]. Thus, road safety is a major societal concern and a constant goal of rules and regulations developed and implemented in the transportation sector [8]. Road safety is one of the major aspects of sustainable urban transport systems [9]. Every year, lack of road safety leads to large numbers of road traffic accidents in different parts of the world. This not only results in large numbers of injuries and deaths, but also causes social-economic and psychological pressures on cities and urban residents. It is, therefore, obvious that paying attention to road traffic safety is essential for achieving sustainable transportation.

It is widely known that the number of road crashes is significantly growing worldwide. In this domain, within the transportation sector, road accident outcomes increasingly result in the loss of lives and injuries [10]. Road traffic accidents are known as one of the most complicated issues all over the world [11]. Traffic accidents and their associated social costs, physical injuries, and human and economic losses are among the negative consequences of increased mobility [12,13]. According to the World Health Organization (WHO), road car accidents were the third leading cause of casualties in 2018 globally [14]. Every year, approximately 50 million people are killed or injured on roads around the world, and car accidents are the eighth leading cause of death [15,16]. Road traffic injuries lead to considerable economic losses to individuals, their families, and to nations as a whole. These losses arise from the cost of treatment, as well as lost productivity for those killed or disabled by their injuries, and for family members who need to take time off work or school to care for the injured [17]. It is true that different countries may have different problems and factors affecting road traffic accidents, as depicted by different studies in various parts of the world [18]. However, according to WHO, more than 90% of road traffic deaths occur in low- and middle-income countries [17]. Environmental factors (weather conditions and visibility), human errors, road characteristics and quality, vehicle design, and the number of vehicles on the roads are critical influencing factors on road traffic accidents [13,17]. Various measures such as implementing educational and regulatory programs and developing efficient transportation infrastructure systems must be taken to reduce car accidents in light of sustainable transport development. However, developing countries are lagging behind in this regard: more than 30% of accident-related deaths in low- and middle-income countries can be attributed to inefficient transportation infrastructure [18].

One of the most common methods of road accident analysis is the use of statistical data recorded at the accident locations. Some studies employ simple methods such as the number of accidents and their classification based on the level of injury [19]. Due to the development of up-to-date tools in the field of spatial analysis, the limitations of using these methods have become more evident. These limitations include, for instance, lack of ability to examine the relationship between space and time, limited ability to identify and rank accident hotspots, and limitations in considering environmental conditions [20]. Additionally, the accident datasets gathered from the traffic police in the form of tables and charts are complicated and not suitable for communication with planners and the public [21]. Therefore, it is essential to use effective spatial-temporal analysis techniques for better analysis of accident datasets [5,22].

In the context of urban traffic accident modeling, various algorithms and methods for the classification of different types of accidents have been developed, of which the density-based methods can be used to determine high-risk areas [22]. Based on the increasing trend of road accidents, it is necessary to identify the accident hotspots. In this context, the locations, which are identified by a high accident occurrence compared with other locations, are known as hotspots or black spots, which can be identified through GIS spatial and network analysis [23].

Recent progress in GIScience, decision-making technologies, as well as international open source databases (e.g., open street maps, Google maps, Otonomo traffic data, etc.) leads us to develop spatiotemporal patterns of road accidents efficiently. Early studies pointed out that the trend of using data assessment and GIS spatial and network analysis as an effective methodology for road traffic mapping [10]. It ought to be indicated that it is growing tremendously and this trend of evaluating traffic accidents is more often employed

by world researchers [24,25]. Thus, applying GIS spatial and network analysis enables us to understand the spatiotemporal variations and intensity of accidents. For this goal, many authors have proposed various approaches to analyzing historical road traffic accident data using GIS analysis [24]. Besides infrastructural factors, accident rates are influenced by weather and seasonal variations. GIS has also been employed extensively in traffic safety studies in many countries [21,22]. While these studies provide temporal analysis of traffic accidents, their results have mainly been presented as simple graphs that are not able to demonstrate the variation in accident clusters over time [23]. A better understanding of both the temporal and spatial dimensions of accidents is needed, as it can provide a more granular depiction of accident hotspots [20].

According to WHO, roads in Iran are generally known to be very unsafe, and the number of road accidents in the country is 20 times the global average [12]. In fact, nearly 17,000 people are killed, and more than 351,000 injured, as a result of traffic accidents in Iran almost every year [12]. Table 1 represents the number of road accident deaths in Iran from 2013–2019. As this table indicates, the number of deaths in road accidents has reduced to 13,703 in 2019. Even though it is still significant, it might be reduced due to the travel restrictions during the COVID-19 pandemic. It is well understood that COVID-19 was one of the main challenges for human society in the past years and is expected to have long-term effects on human life [24–26]. To control and reduce the spread of COVID-19, significant mobility restrictions were applied in many parts of the world that limited non-essential travel in cities [8,27].

**Table 1.** Number of road accidents and deaths in Iran from 2013–2019 [28].

Year	Number of Vehicles	Number of Road Accidents	Number of Deaths
2013	15,752,815	14,488	17,994
2014	18,129,053	13,975	16,872
2015	20,341,520	14,213	16,868
2016	23,581,222	13,875	16,150
2017	26,842,915	14,107	16,509
2018	30,116,599	14,323	17,183
2019	33,680,906	11,408	13,703

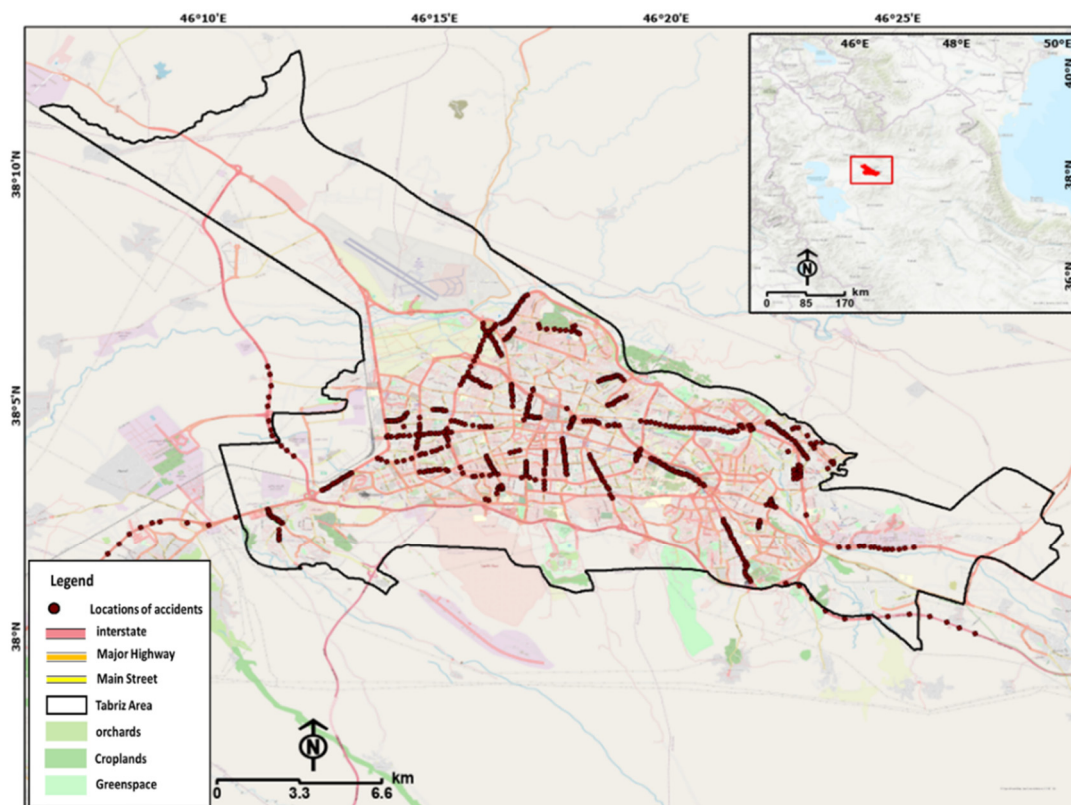
Initial research suggests that COVID-19-related mobility restrictions have led to reductions in traffic accidents on both urban and interurban highways [29–31]. Within the current research, we aimed to analyze the spatiotemporal patterns of urban traffic accidents and observe the impacts of COVID-19 lockdowns on their trends. We also aimed to propose an integrated GIS-based methodological framework to identify the hotspots of urban traffic accidents and their correlation with urban land use and demography characteristics, to support decision making to improve the situation, so that fewer accidents will happen in the future.

## 2. Materials and Methods

### 2.1. Study Area

This study was carried out in Tabriz, which is the capital of East Azerbaijan province in north-west Iran (Figure 1). The city covers an area of 245 km<sup>2</sup> and, with a population of about 1.8 million, is the fourth largest city in Iran. Like the other Iranian metropolitan cities, it has experienced rapid rates of urban development in the past decades. Tabriz is the largest economic center and metropolitan area in north-west Iran [32]. Historically, it has been the capital of several kingdoms and empires through the ages and was known as a major trade center on the Silk Road. Nowadays, its proximity to several countries (i.e., Turkey, Iraq, Azerbaijan and Armenia) and the fact that it is a major hub for industry, commerce and education has made Tabriz a strategically important city. This high concentration of socio-economic activities is a contributing factor to traffic congestion on the highways and inner-city streets in Tabriz. Rapid development without proper consideration of the

necessary supporting infrastructure has led to an increase in risks, including road traffic accidents. According to the Traffic Police of Tabriz, the numbers of traffic-related deaths and injuries have always been high in the city. Table 2 shows the number of deaths and injured people in urban road traffic accidents from 2016–2020. These data clearly show the importance of taking more actions to enhance traffic safety. Tabriz, like Iran’s other major cities, was severely impacted by the COVID-19 pandemic. Since early 2020, the city has been hit by multiple waves of the epidemic, with significant social and economic consequences [26]. According to the Iranian Ministry of Health and Medical Education [33], since the early days of the pandemic, Tabriz has always been a major high-risk city.



**Figure 1.** Location of the study area.

**Table 2.** Number of deaths and injured people in the transport network of Tabriz [34].

Year	Deaths	Injured
2016	118	6218
2017	100	7172
2018	88	7272
2019	100	4981
2020	109	3008

## 2.2. Dataset

The data used in this study include report data of accidents in the city of Tabriz from 2018 to 2020. The data include the address and GPS-based X–Y location of road accidents, obtained from the Traffic Police of Tabriz. In order to consider the seasonal climate characteristic of the city on urban traffic accidents, the data were classified into winter, spring, summer and autumn seasons from 2018 to 2020. The data were categorized based on the type of accident, casualties and season, and are presented in Table 3. To analyze the spatial correlation of urban traffic accidents with demography and land characteristics of the study area, recent land use maps and statistical block maps with demography details were received from Tabriz Municipality 2021 (Table 4).

Table 3. Road Traffic Accident Reports [34].

Time Division			Trash Type				Injury Type			
Year	Season	Month	Damage	Injury	Death	Accident Total	Driver	Pedestrian	Passenger	Total Injury
2018–2019	Spring	April	155	144	0	511	69	59	50	180
		May	178	210	1	399	79	73	92	245
		June	190	228	1	440	99	78	84	262
	Summer	July	198	264	0	462	93	60	95	248
		August	222	251	2	475	82	74	104	260
		September	239	207	3	449	65	56	87	208
	Autumn	October	230	206	3	439	68	63	79	210
		November	259	197	2	458	59	43	88	190
		December	290	220	1	511	58	73	102	233
	Winter	January	300	209	2	419	63	68	84	215
		February	260	136	4	389	52	45	59	156
		March	257	182	1	419	70	52	83	205
2019–2020	Spring	April	145	137	2	284	67	51	59	177
		May	203	159	2	363	74	43	65	182
		June	213	165	3	381	70	56	74	199
	Summer	July	237	226	2	465	125	77	89	291
		August	275	226	0	501	99	73	93	265
		September	198	207	1	406	103	50	77	230
	Autumn	October	110	164	4	278	82	46	70	198
		November	36	165	6	207	63	43	62	168
		December	25	149	3	177	65	31	60	157
	Winter	January	21	139	0	160	50	49	50	149
		February	41	116	1	158	41	27	53	121
		March	22	107	2	131	62	34	31	127
2020	Spring	April	19	68	6	98	34	20	22	76
		May	21	104	4	127	61	29	26	116
		June	10	99	2	112	47	26	33	105
	Summer	July	9	91	1	101	54	25	31	111
		August	14	131	6	151	67	27	48	142
		September	30	184	5	219	82	52	70	202
	Autumn	October	25	143	2	170	65	31	50	146
		November	1	88	3	92	51	31	28	110

### 2.3. Methodology

In this study, we aim to propose an integrated GIS-based approach to identify the spatial and temporal vulnerability to the risks of urban traffic accidents in Tabriz using road accident data and to explore the spatiotemporal relationship of seasonal accident density. For this purpose, accident data for April 2018 to November 2020 were obtained from the Traffic Police of Tabriz city. The research methodology was established based on the GIS spatial and network analysis. To evaluate the impact of COVID-19, the seasonal changes of car accidents were used as a time dimension to analyze the decrease and/or

increase in the number of urban traffic accidents. The severity index (SI) was applied to analyze the severity of injuries caused by the accidents. In other words, the SI allows us to examine the spatial-temporal patterns of urban traffic accident hotspots in Tabriz during different seasons. This index has been used by the Belgian government to determine the severity of each accident using different coefficients for different types of crashes [35]. Finally, we examined whether there is any association between the accident rate, land use and population density. To visualize the spatiotemporal data, an integrated approach of the GIS-based Comap method was applied. The Comap method is an effective technique to visualize multivariate data to detect the spatiotemporal patterns within complex data [36]. In addition, the SI was also employed to recognize the high-risk regions using accident data. Then, using the kernel density estimation (KDE), high-intensity areas were obtained based on the calculated index, and the accident hotspots were identified. Eventually, using demographic and land use data for Tabriz city, areas with a high risk of road accidents were identified. Figure 2 shows the flowchart of different methods used in this research.

**Table 4.** Land use and demography data from Tabriz Municipality 2021.

Data	Class	Scale and Details
Land use	Administrative educational Services	update data in the scale of 1/2000
	Urban Facilities	
	Commercial	
	Recreational	
	Industrial	
	Residential areas	
	Agriculture and Livestock Transportation	
Demographics	Population Density (inhabitants/km <sup>2</sup> ?)	16–125
		126–206
		207–369
		370–756
		757–2089
	Age	0–10 (232,431)
	11–20 (320,243)	
	21–35 (394,948)	
	35–45 (302,204)	
	>45 (234,310)	

### 2.3.1. Urban Traffic Accident Hotspot Analysis

We carried out a GIS-based hotspot analysis to determine the location of urban traffic accidents. The intended data include the number and location of accidents by type of accident, who was injured (driver, pedestrians and/or passengers), and the number of casualties (Table 3). Based on the data presented in Table 3, to gain an initial understanding of the general situation of accidents in Tabriz, the total number of accidents and injuries in different areas in the 2018–2020 period was analyzed and presented in Figure 3. Furthermore, to compare the urban traffic accident data with the population density characteristics and land use/cover patterns, the relevant maps were obtained from the Tabriz Municipality and analyzed, as shown in Figure 4.

### 2.3.2. Comap Method

The Comap method aims to visualize changes to spatiotemporal patterns over time [37]. The basic idea is that a bivariate subset of raw data is selected based on certain conditions (e.g., a defined rainfall range or a categorical variable such as weekend or weekday). This data is then plotted either in raw form in a scatter plot panel or as a mapped kernel density surface [38]. The Comap tool is essentially a geographical variant of the coplot and allows a graphical exploration of the data to analyze the relationship between a pair of variables

based on a third variable (and perhaps also a fourth). In the Comap, the first pair of variables represent a geographical location, and the graphic technique is adapted to reflect this [38]. We computed the seasonal variation in the locations of urban accident to carry out the impact of the season on the spatiotemporal patterns of accidents.

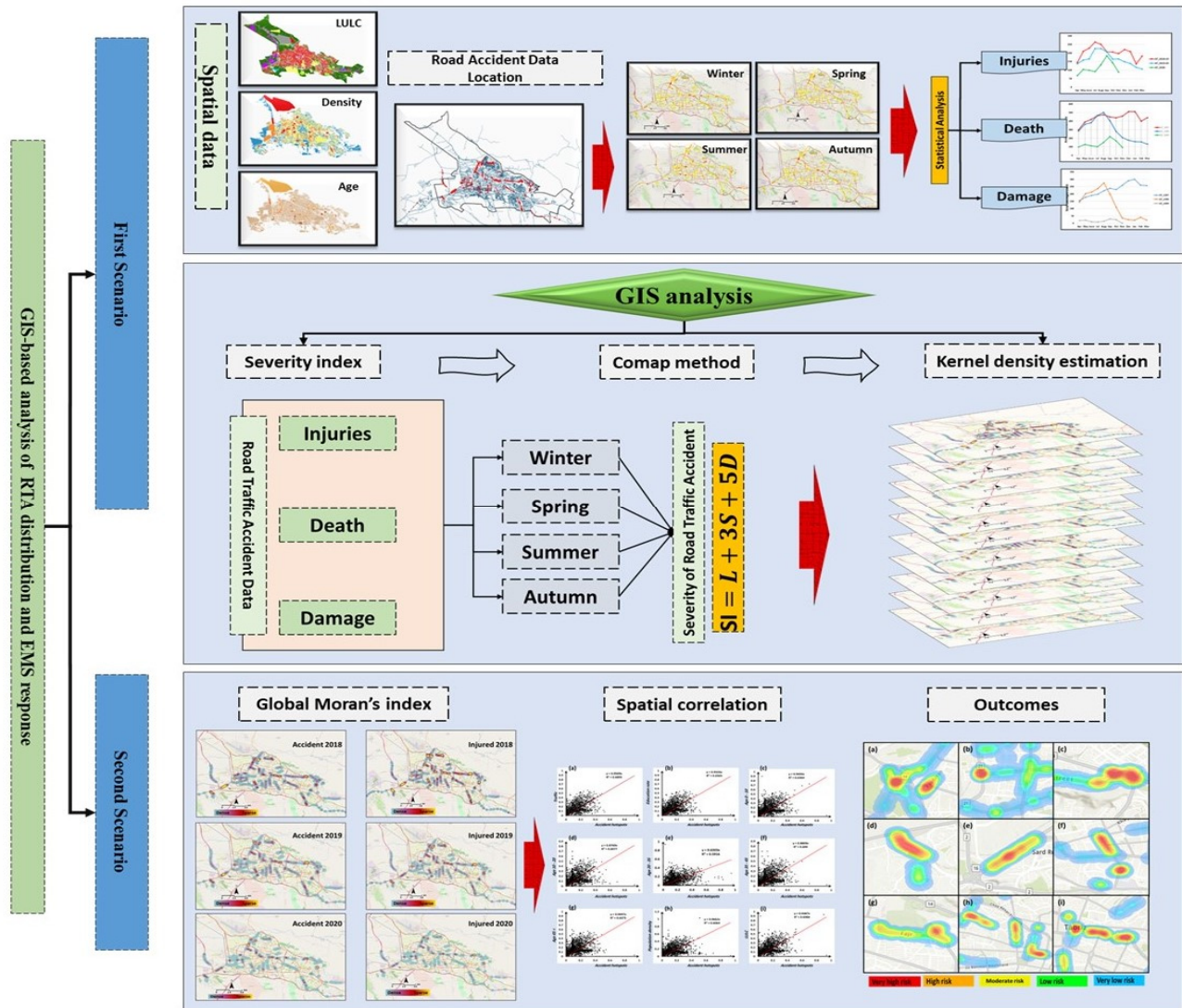


Figure 2. Main steps for the implementation of the research methodology.

### 2.3.3. Severity Index

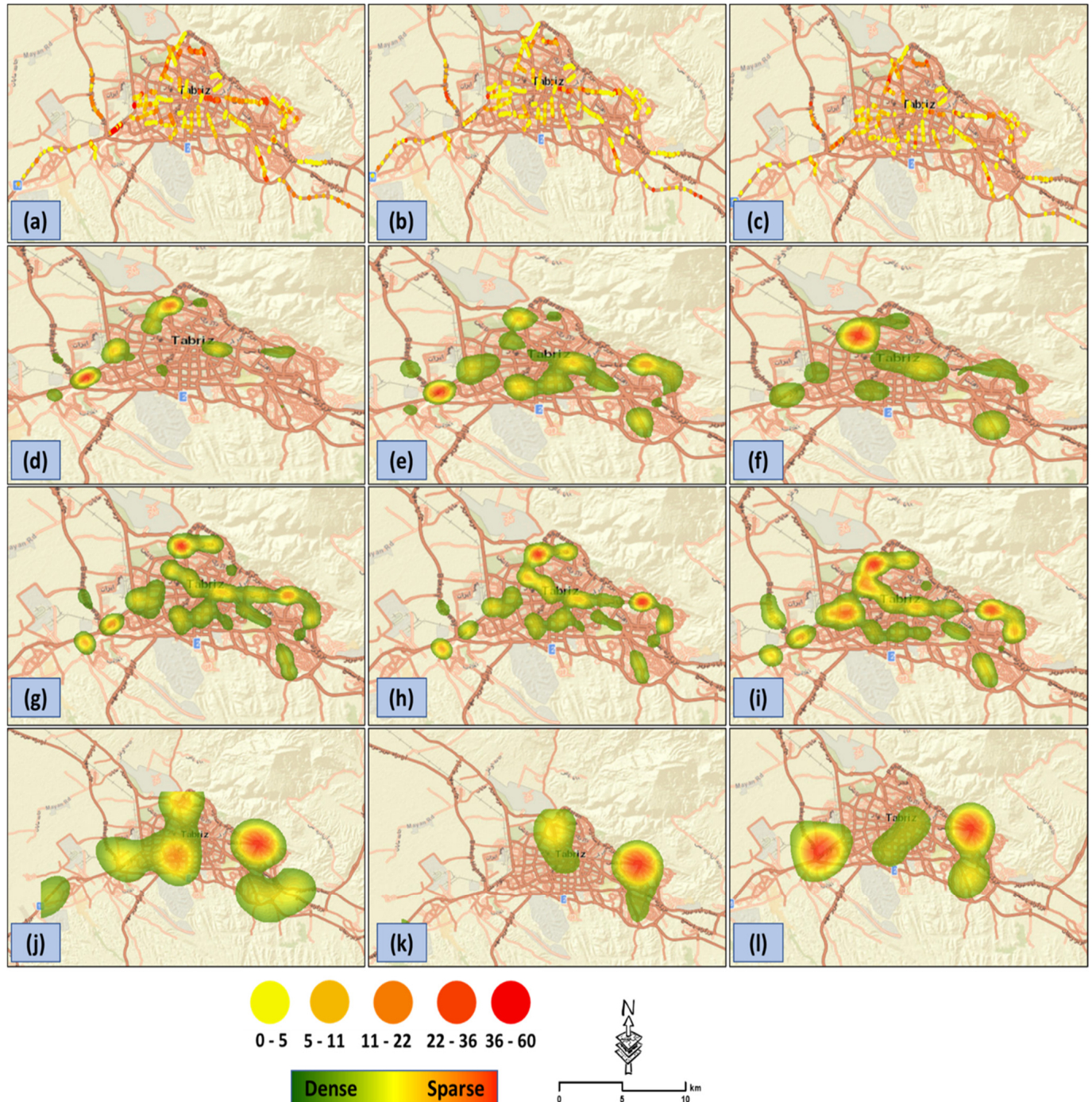
The severity index (SI) is used to determine and express the distribution of different types of urban traffic accidents, as well as injuries and deaths. The SI approach allocates a higher impact score to more serious accidents, but not with the extremely high values, and calculates an indirect rate to the cost of accidents [20]. According to Geurts et al., (2004) [35], the SI for each location can be calculated using Equation (1):

$$SI = 1L + 3S + 5D \quad (1)$$

where SI is the severity index for each location;  $L$  is the total amount of slight injuries;  $S$  is the total number of serious injuries (including drivers, passengers and pedestrians); and  $D$  is the total number of deaths (including drivers, passengers and pedestrians [35]. To apply the severity index to accident risk, the data were first categorized by year, season and month (Please see Table 3). Accordingly, the desired columns were determined to calculate

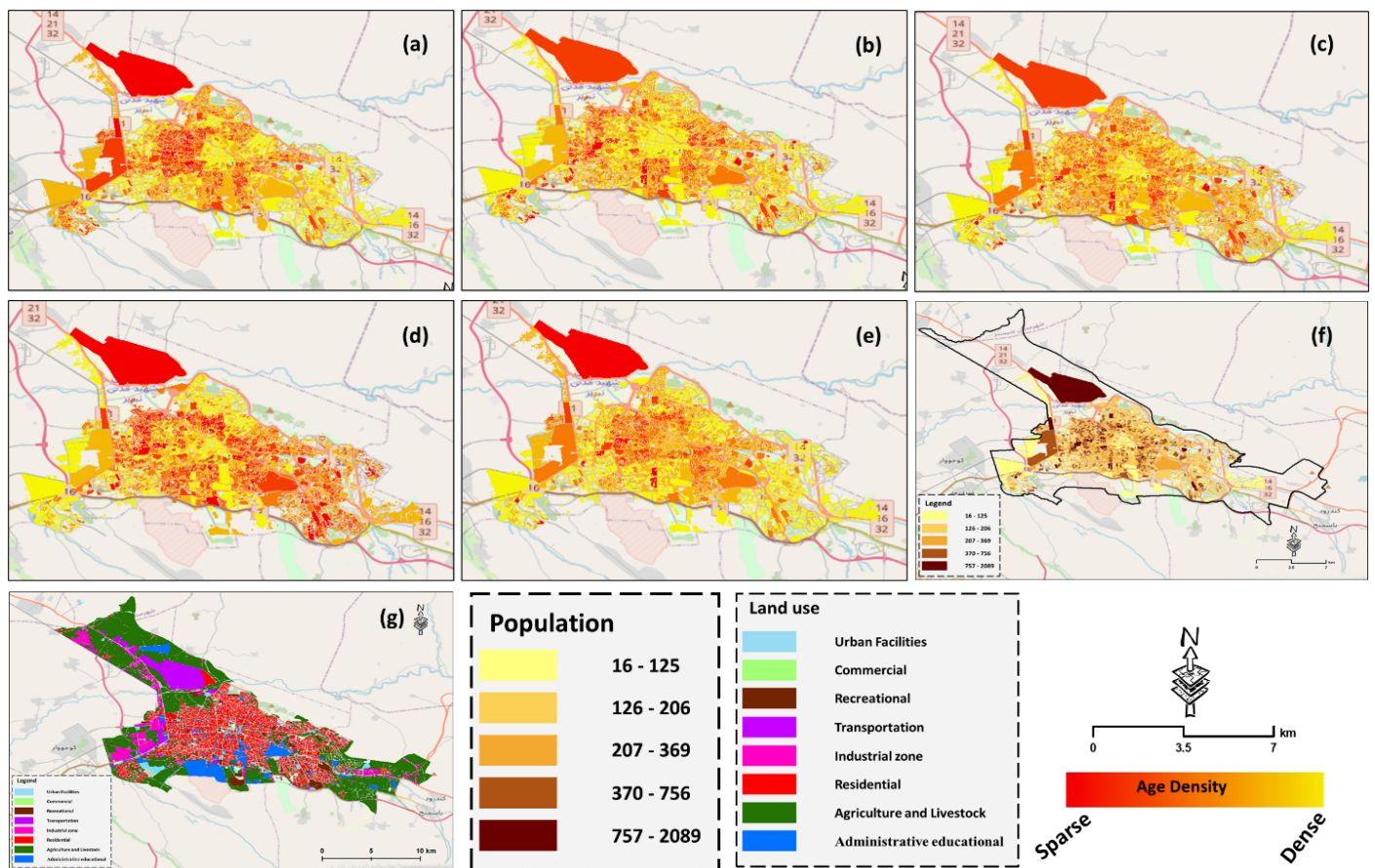
the index and the desired index was calculated in the GIS environment using Equation (2), as follows:

$$SI = (1 \times [\text{Damage Accident}]) + (3 \times [\text{Iries Total}]) + (5 \times [\text{Death Total}]) \quad (2)$$



**Figure 3.** General distribution of the frequency of accidents and injuries in Tabriz from 2018 to 2020, including: (a) Total number of accidents in 2018, (b) Total number of accidents in 2019, (c) Total number of accidents in 2020, (d) Damage density in 2018, (e) Damage density in 2019, (f) Damage density in 2020, (g) Injuries density in 2018, (h) Injuries density in 2019, (i) Injuries density in 2020, (j) Death density in 2018, (k) Death density in 2019 and (l) Death density in 2020.





**Figure 4.** Land use and demography maps: (a) Age 0–10, (b) Age 10–20, (c) Age 20–35, (d) Age 35–45, (e) Age 45+, (f) Population Density based on number of people and (g) Land use map.

### 2.3.4. Kernel Density Estimation Technique

The kernel density estimation (KDE) can be applied as a nonparametric density estimation technique in the GIS environment. As a common GIS algorithm, the KDE can be used to create a density map based on the hotspots of car accidents to show the density of the accident points. The KDE method can impressively reduce the impact of noise by allocating equal noise to the input data [39]. In fact, the GIS-based KDE is the most popular method for identifying high accident risk locations on the road networks and has been employed by numerous researchers [40–49]. Thus, applying the KDE enables us to calculate the severity of risks within an accurate research bandwidth in the study regions to generate a smoothed surface.

Within this research, after computing the accident risk severity index for each location, the KDE method was used to identify the regular clusters and accident risk hotspots and to display the results. Therefore, a kernel function is used to allocate a weight to the region surrounding the events proportionate to its distance to the point event. From there, the value is highest at the point event center and decreases smoothly to a value of zero at the radius of the research circle. At the end, a smoothly continuous intensity surface is created by adding the individual kernels in the research region [50]. The density at a defined position is computed using Equation (3), as follows:

$$f(x, y) = \frac{1}{nh^2} \sum_{i=1}^n k\left(\frac{d_i}{h}\right) \quad (3)$$

where  $f(x, y)$  is the estimated density at the location  $(x, y)$ ;  $n$  is the number of observed urban traffic accidents;  $h$  is the bandwidth or kernel size;  $K$  is the kernel function; and  $d_i$  is

the distance between the location  $(x, y)$  and the location of the  $i$ th observation. The output of the KDE method was presented in a raster format. Several researchers declare that the selection of the bandwidth  $r$  is more important than the selection of the kernel function  $k$  [50–53]. Technically, three kernel functions can be used to conduct the KDE, namely the Gaussian function, the Quartic function and the Minimum variance function  $b$  [54]. It is well understood that the sectional efficient function should be based on the context of the dataset, such as spatial distribution, standard deviation, etc. Within this study, the Gaussian function was applied based on the continuous context, spatial distribution and major trend of the urban traffic accident dataset. Finally, after identifying areas with a high percentage of traffic accidents, we correlated these areas with a population density analysis to analyze the most vulnerable age group of the injured population. Furthermore, the land use types in areas with a high road accident risk in Tabriz were determined and presented.

### 2.3.5. Global Moran's Index

The Moran's I Index, is one the most efficient spatial autocorrelation assessments in the GIS environment [52,55]. Basically, it is used to investigate spatial location in order to determine whether nearby areas have similar or dissimilar values [52,56]. Moran's I value ranges from 1 to  $-1$ . The number near 1 indicates grouped patterns in areas with similar values (high or low), whereas the value around  $-1$  indicates dispersed patterns. Random patterns are indicated by a value approaching zero [57]. Spatial correlation is a measurement of spatial dependency between the values of random variables in different geographical regions [58]. The Moran's I spatial autocorrelation index is calculated using the following Equation (4):

$$I = \frac{N \sum \sum_{wij} (x_i - x^-)(x_j - x^-)}{w \sum (x_i - x^-)^2} \quad (4)$$

where  $x_i$  is relative or distance correlation in area units of  $i$ ;  $N$  is the number of area units; and  $w_{ij}$  stands for weight [52]. The global Moran index is frequently used to depict a spatial relationship and correlation assessment in the GIS environment. The geographical distribution measurement highlights a complicated distribution and spatial patterns of urban traffic accidents. It can be used to explore the values indicating same data distribution features, such as centrality, density and data orientation. We employed the Global Moran's index to analyze and carry out the location of urban traffic accidents with impact indicators such as land use and population density.

## 3. Results

### 3.1. Trend Analysis of Urban Traffic Accidents

Our results show that in high population density areas, the number of accidents is high, that most of the accidents are of the injury type, and that most of the injured people were pedestrians. In terms of the land use type, industrial and administrative areas, as well as educational and medical centers, were recognized to be more vulnerable due to high vehicle traffic volumes. As indicated earlier, weather conditions may also have a significant impact on urban traffic accidents. Thus, we examined the impact of the different seasons on the results. The results showed that in 2018, the autumn and winter seasons had the highest number of accidents. However, in the winter season of 2020 (January to March 2020), due to the outbreak of COVID-19 and the implementation of traffic restrictions, a significant decrease in urban traffic accidents was observed compared with the corresponding seasons in 2019. Due to the decrease in the number of accidents, the number of injuries also decreased dramatically (Figure 5). To visualize these changes, the hotspot map of car accidents and the distribution of casualties is shown in Figure 6. Considering the main purpose of the study, which was to investigate the spatiotemporal trend of road accidents in Tabriz, all seasons of the year were taken into account. According to Figure 5, the number of urban traffic accidents decreased in 2020, despite the climatic

conditions that were expected to lead to an increase in accidents in winter (Figure 7). The main reason for this counter-intuitive trend was the decrease in traffic as a result of the restrictions on commuting in an effort to slow the spread of COVID-19.

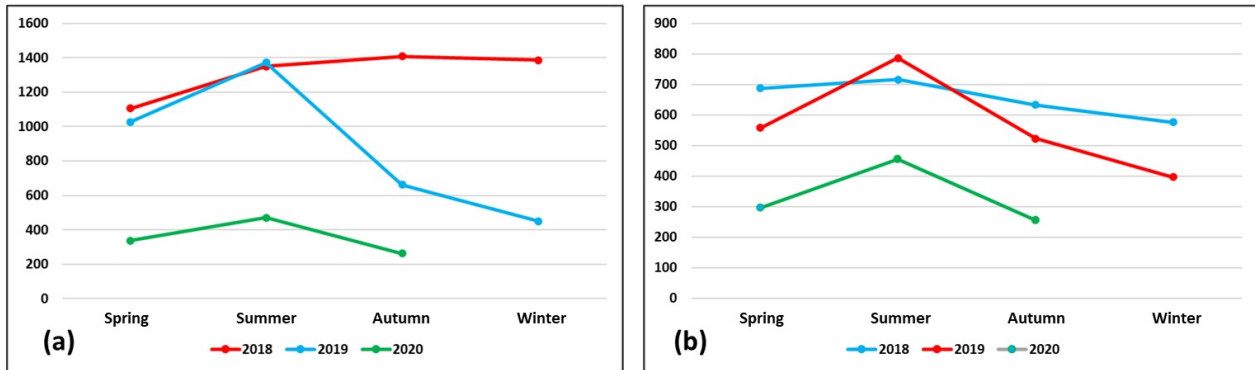


Figure 5. The trend of urban traffic accidents from 2018 to 2020 in Tabriz: (a) Variation in the number of accidents and (b) Variation in the number of injured people.

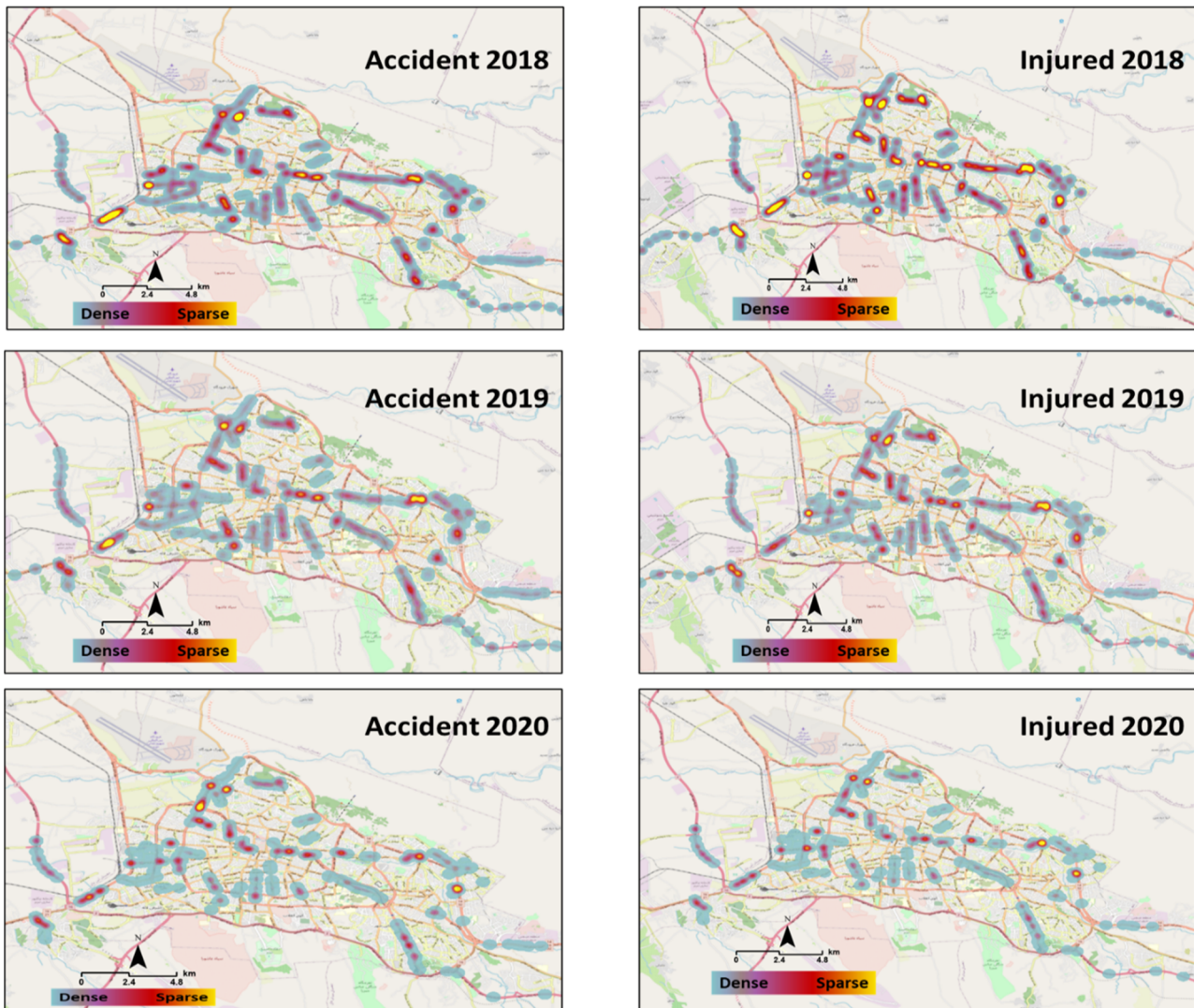
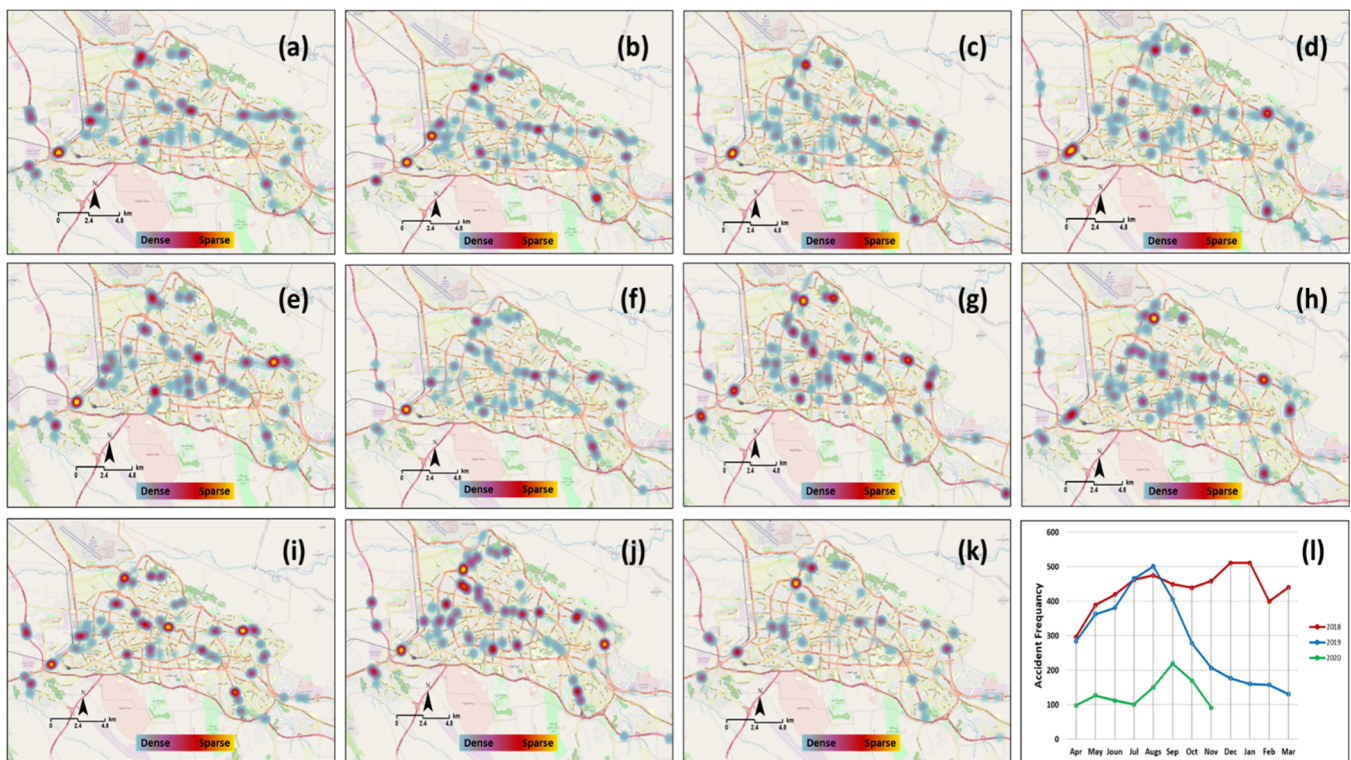


Figure 6. Urban traffic accident hotspot maps for the observed accidents and injuries from 2018 to 2020.



**Figure 7.** Seasonal spatiotemporal variation in urban traffic accidents: (a) Spring 2018, (b) Summer 2018, (c) Autumn 2018, (d) Winter 2018, (e) Spring 2019, (f) Summer 2019, (g) Autumn 2019, (h) Winter 2019, (i) Spring 2020, (j) Summer 2020, (k) Autumn 2020 and (l) Annual variation chart.

### 3.2. Applying the Severity Index to Analyze the High-Risk Areas

The results of this analysis show that, although the number of accidents is higher in spring than in winter, the rate and intensity of winter accidents and injuries is more severe (Figure 8). According to Figure 8, there were 1105 accidents in the winter of 2018, which is significantly reduced to 449 in same season in 2019. The results are similar when comparing the number of accidents in the spring of 2018—1350 accidents—against the same season in 2019, with a total of 1028 accidents. From the geographical perspective, this figure clearly indicates that the urban road network in northern areas of the city were more vulnerable to urban traffic accidents. According to the results, the urban road traffic accident hotspot analyses with and without a severity index yielded relatively similar hotspots, but the rankings of some hotspots were quite different when considering the accident SI. After analyzing the ranking, the effect of the accident SI on the results can be easily observed.

Figure 9 represents the hotspot analysis of urban traffic accidents in Tabriz. This figure represents the aggregated spatial pattern of urban traffic accidents in the city and also vulnerability in the urban road network of the city. It is well understood that the spatial pattern of urban traffic accidents might be affected by relevant factors, such as urban road traffic, demographic characteristics and urban land use patterns. Figure 10 represents the spatial pattern of the relevant impact indicators. Figure 11 also represents the correlation of urban traffic accidents with relevant impact indicators. An overview of the urban traffic accident hotspot analysis and its correlation with impact indicators acknowledges the significant impact of relevant indicators (Figure 11). Results of these analyses demonstrate that the areas with a high population of the 0–10 age group are mostly located in the northern, western and partly southern areas of Tabriz, and are more vulnerable. Those in the older than 45 age group are mainly concentrated in the central areas of the city that offer better access to services and medical facilities. This makes these areas more vulnerable for the older than 45 age group. The correlation between the severity of road traffic accidents and land use types reveals a more significant relationship between accident severity and

industrial and residential areas than other land use types. Finally, to identify the areas with a high severity of road traffic accidents, an enlarged image of high-intensity locations is shown in Figure 12.

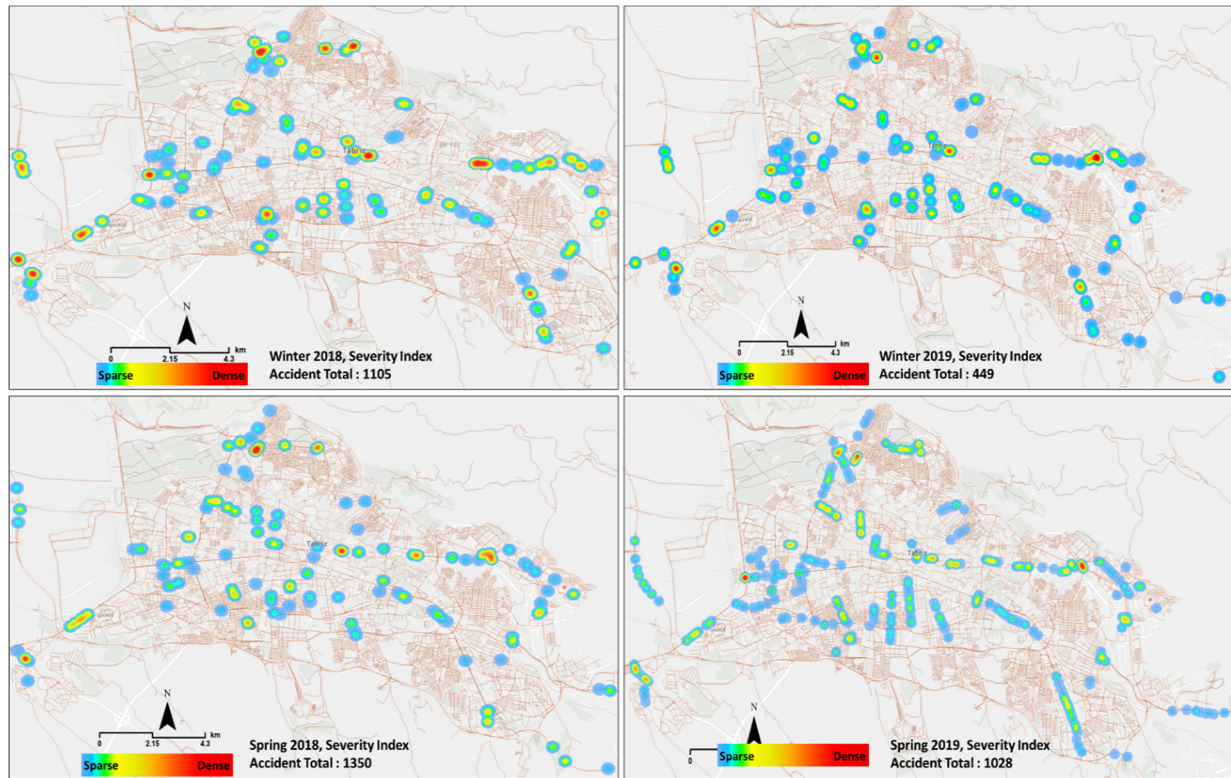


Figure 8. Spatiotemporal variation of car accidents based on the severity index.

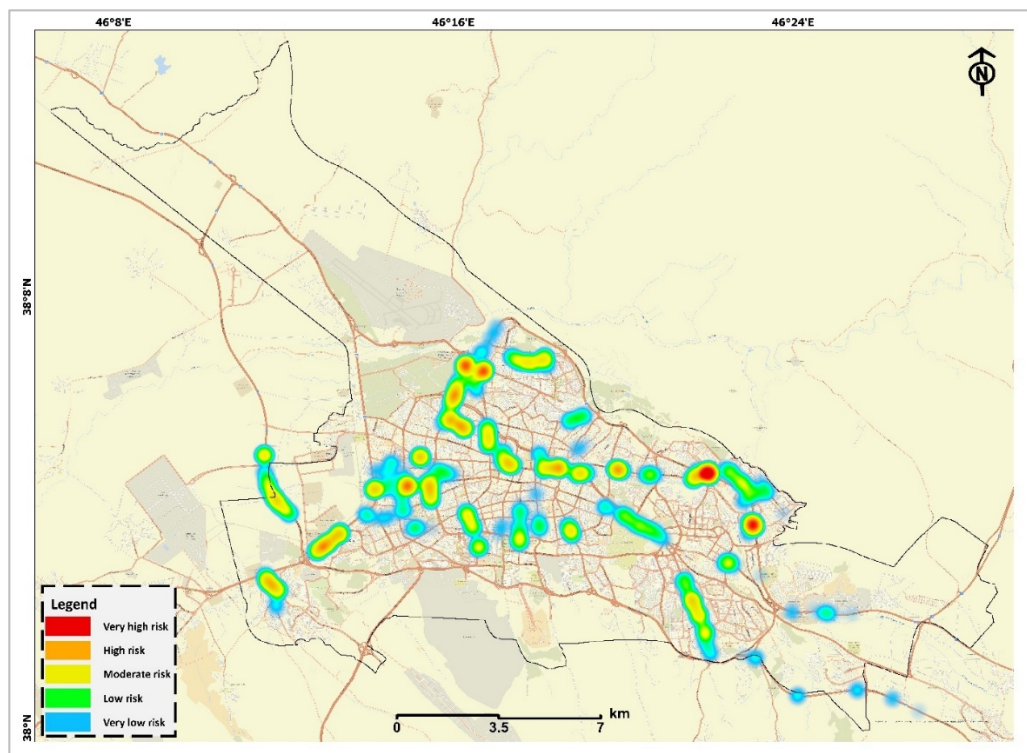
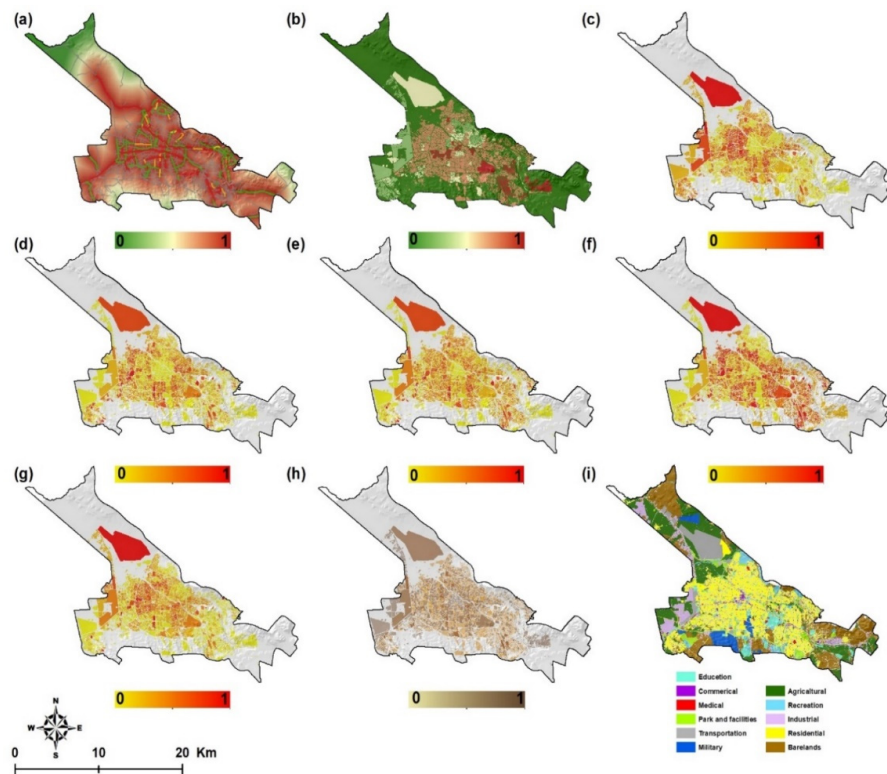
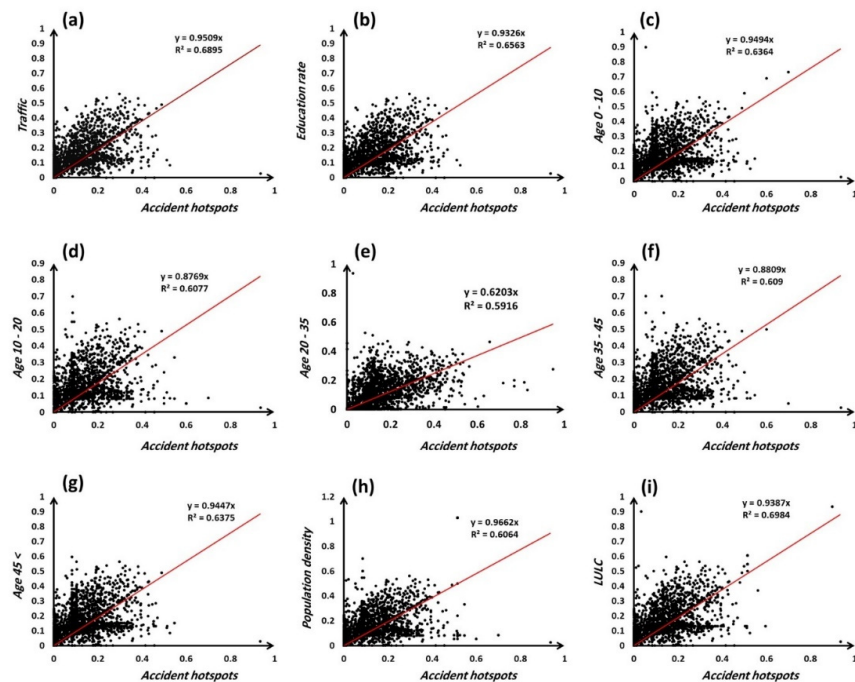


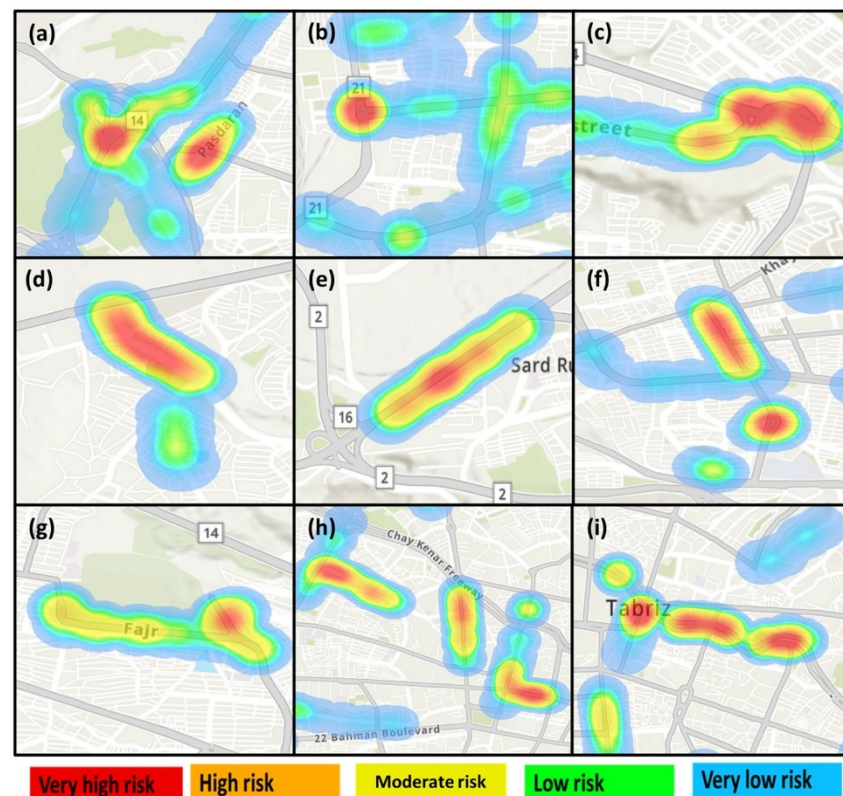
Figure 9. Results of the aggregated hotspot analysis of urban traffic accidents in Tabriz.



**Figure 10.** Spatial distribution of the impact indicators of urban traffic accidents, including: (a) urban road traffic, (b) educated population, (c) population in age group 0–10, (d) population in age group 10–20, (e) population in age group 20–35, (f) population in age group 35–45, (g) population in age group 45<, (h) population density and (i) urban land use/cover.



**Figure 11.** Results of the spatial correlation assessment of the aggregated urban traffic accidents and relevant impact factors, including: (a) urban road traffic, (b) educated population, (c) population in age group 0–10, (d) population in age group 10–20, (e) population in age group 20–35, (f) population in age group 35–45, (g) population in age group 45<, (h) population density and (i) urban land use/cover.



**Figure 12.** Road network of Tabriz where the severity of urban traffic accidents is high, including: (a) Azerbaijan Square, (b) Rahahan Square, (c) Shahid Fahmideh Square, (d) Velayat Blvd (An-dishes), (e) Sento Caddesi, (f) Abureyhan Blvd, (g) Fajr Street and Kowsar Blvd, (h) Gajil Square and (i) Chaykenar Street.

#### 4. Discussion

We used GIS-based analysis to better understand the spatiotemporal patterns of urban traffic accidents. According to the results, GIS presents the most demanding tools used to analyze road accidents and road design that can be noteworthy in traffic accident prevention. From the methodological perspective, our results indicate that integration of GIS-based analysis, Comap and SI could support each other to efficiently analyze the hotspot patterns of the road accidents. In addition, the Global Moran's index and Kernel Density Estimation also lead us to develop the spatiotemporal pattern of the accident efficiently. According to Giang Le et al. [11], SI and Comap analyses determined the relatively similar hotspots on their study, but they also found that rankings of some hotspots might be different due to the integration of accident SI, easily investigated, which is also approved in this study. Early studies pointed out several multidimensional techniques and methods, and particularly the Kernel density estimation, that have been implemented for GIS-based road accident analysis [10]. However, our analysis indicated that the Kernel density estimation as a standalone method for road accident mapping might face some sort of uncertainty and ambiguity regarding the precise location of a road crash, which is also acknowledged in some studies, e.g., [11,59]. Thus, its integration with GIS, and particularly together with Global Moran's index, leads us to improve the efficiency of results.

This proved effective in identifying risk hotspots in the city of Tabriz. Results show that areas where industrial uses are dominant (i.e., the fringe areas of the city) are major urban traffic accident hotspots with a severe risk of accidents. For instance, the presence of various industrial complexes such as the Petrochemical Company, Oil Refinery, Tractor Manufacturing Company and other industrial complexes on the fringe of the city and along the Tabriz–Azarshahr road, as well as the lack of effective traffic management systems, has

increased the accident risk in these areas. The accident risk in the fringe areas could also be attributed to the fact that the city is encircled by major highways that form a beltway. Since Tabriz is an industrial hub in a central position in north-west Iran, these highways play an essential role in reducing the inner-city traffic volumes. However, due to inappropriate design, points of intersection of these highways with other major and local roads/streets experience large volumes of traffic congestion and are also risk hotspots. These include, for instance, major urban squares such as Azerbaijan, Rahahan and Shahid Fahmideh.

However, accident hotspots could also be observed in some of the inner-city areas. Some high-risk inner-city areas are located in the vicinity of major roads such as the inner beltway and the Chaykenar throughfare, where traffic volume and average vehicle speed is high. Particularly, the risk of accident is high at points of intersection between these major roads and local roads. In addition, some hotspots could also be observed in areas with a high concentration of commercial and administrative uses. For instance, traffic volumes have always been high in the areas neighboring the bustling Tabriz Bazar. These areas also host major administrative entities such as the provincial government building and the city hall. While some measures, such as odd-even traffic restriction and the expansion of the public transportation system, have been taken to reduce traffic volumes, limited success has been achieved due to the major preference towards private cars. In fact, a large share of vehicles on Tabriz streets are single occupancy vehicles and public transport modes are mainly used by those who cannot afford a private car. While a large traffic volume in itself does not result in more accidents, it can cause problems when combined with other common issues (in Tabriz), such as poorly maintained road infrastructure, ineffective vehicle inspection (to ensure compliance with safety standards), poor enforcement of traffic regulations, and citizens' limited attention to traffic safety rules and regulations. Comparing urban traffic accident hotspots against demography indicated that the younger than 10 years and older than 45 years age groups were the most vulnerable to road accidents.

According to recent investigations related to the age of accident victims, children and the elderly are the most affected groups [59]. Thus, in this study, we used the population density layer of population aged from 0–10 and over 45 years to examine the relationship between age and the severity of accidents. In addition to age, we also considered population density, which is discussed in the methodology section. Areas with dense population can be more prone to pedestrian accidents, leading to a higher number of deaths and injuries. Car traffic in different areas of the city, in addition to the time of day, depends on the land use type. For instance, in areas where industrial complexes, refineries, factories, or service centers are located, traffic is heavier, and the number of accidents is likely to be higher. Thus, the areas with a high risk of road traffic accidents were also analyzed according to the land use type.

It is well understood that sustainability in urban transport has been one of the major aspects of urban sustainable development. The purpose of sustainable transportation is to ensure that environmental, social and economic factors are considered when making transportation-related choices [6]. Basically, the sustainable urban network should be developed based on the 'right to mobility for all' and 'right to the city', as pointed out by [27,60]. Technically speaking, any sustainable urban transport network should support efficient, safe and ecological mobility for citizens [61]. Results of this study and analyzing urban traffic accidents show that the urban transport network in Tabriz is not developed in a sustainable manner. The preconditions for transport safety include the recovery and growth of urban public space through the creation of coherent and wide networks of pedestrian and traffic calming areas, bicycle routes and shared spaces [62]. Finally, an anthropocentric, integrated, multimodal, intelligent and sustainable transportation system is more likely to absorb the shocks of climate, environmental, financial, or health crises, as well as meet citizens' immediate and long-term mobility and accessibility needs [27].

One major aim of the study was to examine the impacts of the COVID-19 pandemic on urban traffic accidents. The temporal analysis of the road traffic accident risk showed that COVID-19-related lockdowns and mobility restrictions have significantly decreased the



number of urban traffic accidents. While 1227 accidents were reported for the winter of 2019, the corresponding number for 2020 was 449. Similarly, the number of urban traffic accidents in the spring of 2020 was 337, which is significantly lower than the number reported for the corresponding period in the previous year (1028 accidents). Similar results have also been reported in France, where the number of accidents and serious injuries was reduced by about 40% and 44% during 2020 and 2019, respectively. Traveling by car reduces the risk of COVID-19 contagion, and the dramatic reduction in traffic during the lockdown has made driving a compelling option for those remaining on the road. Crash-related deaths and serious injuries have decreased as the number of kilometers driven has decreased [27]. As Saladié et al. [11] pointed out, COVID-19 could serve as a catalyst for a shift in mobility policies (particularly in cities) toward more environmentally friendly and citizen-centered solutions. Thus, analyzing the social and environmental impacts of COVID-19 could be useful for highlighting major socio-economic and environmental problems that need to be addressed. For instance, there is a lot of research showing that COVID-19-related mobility restrictions have resulted in major air quality improvements in many cities around the world [31].

## 5. Conclusions

The results of this study highlight the urban road traffic accident hotspots in Tabriz and show changes in the total number of urban traffic accidents due to COVID-19-related mobility restrictions. While the results indicating a COVID-19-induced reduction in urban traffic accidents are not surprising considering the significant mobility restrictions in response to the pandemic, they indicate that reducing the number of vehicles on the roads could provide safety benefits. This could provide an opportunity for planners and policy makers to strengthen the case for public transportation by communicating the socio-economic benefits of restricting private car use. As mentioned, this may also provide other benefits such as air quality improvement. This is an issue that needs to be studied further in future.

From the perspective of sustainable urban planning, as results of urban road traffic accidents show, the urban transport network of Tabriz faces a number of challenges, as there is a high number of very high-risk areas that need attention. Based on the results, the number of serious and fatal accidents in Tabriz is significant enough to draw decision makers' and authorities' attention to the matter. We suggest that urgent planning and design measures should be taken to improve conditions in the risk hotspots identified in this study. Therefore, those areas should be prioritized in municipal efforts aimed at enhancing traffic safety. Based on the results, and in order to develop an efficient and sustainable urban transport network, we suggest that there is a need for enhancing traffic safety near the points of intersection between major roads (i.e., highways surrounding the city and the inner beltway) and local roads. Better attention to pedestrian-oriented development around such points is needed. Enhancing pedestrian environments should also be prioritized in other areas such as the city center (near the city's old Bazar), where the high traffic volume and other factors, such as ineffective street design and traffic management, have increased the accident risk. Finally, further investment in public transportation infrastructure and measures to increase public transport use could also be effective in reducing urban traffic accidents. Thus, we conclude that the results benefit urban decision makers and authorities (e.g., Municipality of Tabriz, Traffic Police of Tabriz) in understanding the risk hotspots in the transport network of the city and taking actions to make them safer. In this study, we proposed a state-of-the-art integrated GIS-based spatiotemporal approach for road traffic hotspot mapping. From the methodological perspective, we conclude that applying a GIS spatial and network analysis is an effective and efficient method for spatiotemporal modeling of urban traffic accidents. In particular, since traffic safety has become a major issue in large cities around the world, the proposed approach can be applied in other contexts to identify risk hotspots and take actions to create safer transport networks.

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