



Road Safety and Simulation 2026 – RSS2026

# Fatality Patterns in Attica: A Multi-Method Study of Trends, Clusters & COVID-19 Disruptions

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## Abstract

This research integrates multiple analytical methods to study road fatalities in Attica, Greece, for the period 2016–2022, examining fatality patterns, the influence of COVID-19, and temporal trends.

Descriptive analytics were used to summarise annual and categorical distributions, highlighting key risk groups and temporal fluctuations. Hierarchical clustering was applied to identify structural patterns among fatality categories based on their temporal evolution. A pre-/post-COVID comparison using two-sample t-tests assessed mean shifts across categories, and simple linear regression models characterised fatality trends over time.

The statistically significant findings from the COVID comparison are a decrease in children killed ( $p=0.01$ ) and an increase in single-vehicle crashes ( $p=0.03$ ) in the post-COVID period. Non-national riders showed a large descriptive increase of +74% that did not reach statistical significance ( $p=0.99$ ). Descriptive results confirm persistently high fatality counts among motorcyclists and pedestrians, with most incidents occurring within built-up areas and during nighttime conditions.

These analyses provide a comprehensive insight into fatality dynamics in Attica and underscore the value of combining descriptive, clustering, and inferential approaches for regional road safety monitoring. The findings are consistent with Safe System principles and highlight the need for targeted interventions addressing vulnerable road users, post-COVID behavioural shifts, and long-term trend monitoring within Greece's road safety strategy.

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Peer-review under responsibility of the scientific committee of the Road Safety and Simulation 2026 – RSS2026

*Keywords:* road fatalities; clustering; COVID-19; trend analysis; integrated methodology; descriptive analytics; road safety

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## 1. Introduction

Public health and societal challenges are affected deeply by road traffic fatalities, especially in urban areas where exposure, infrastructure complexity, and transport diversity converge. Road crashes are one of the leading causes of death worldwide. Road traffic injuries claim more than 1,35 million lives and more than 50 million injuries each year (WHO,2018). Despite the contributions of policy interventions, the issue of high fatal road crashes remains a global challenge. The “Safe System” approach is a comprehensive strategy for preventing road deaths and injuries by designing road transport systems that consider the entire system, such as safe road users, safe vehicles, safe speeds, safe roads, and post-crash care (OECD/ITF, 2020). In 2020, Greece recorded 584 fatalities and 518 serious injuries in road crashes. Greece, compared to other European countries, continuously records high rates of death and is subsequently ranked the worst-performing member state on road traffic mortality (Stipdonk et al., 2025). The coronavirus pandemic (COVID-19) has disrupted everyday life and traffic conditions

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globally since its first appearance in Wuhan, China, in December 2019 (Jiang et al., 2020). The World Health Organization (WHO) declared COVID-19 a worldwide pandemic in March 2020. The declaration of the pandemic caused unprecedented crises in mobility systems, law enforcement regimes, and road user behavior. Studies conducted in Greece observed a reduction in fatalities at the beginning of the lockdown (Wegman & Katrakazas, 2021). These dynamics highlight the importance of utilizing multi-method analytical frameworks to capture both structural and temporal changes in crash patterns.

Considering all the aforementioned facts, this research analyses road fatalities in Attica, Greece, between 2016-2022 through an integrated analytical design. First, the analysis begins with descriptive analytics to summarize the yearly and categorical distribution of the variables. Then it proceeds with hierarchical clustering analysis to identify hidden patterns in road accident fatality data. Finally, inferential statistical methods were used to classify trajectories of categorized road accident fatality percentages, including pre- and post-COVID-19 comparison analysis and trend regression modelling. Therefore, it matches Safe System thinking and combines study observation principles with pattern detection and trend monitoring for regional road safety strategy and policy implementation.

The paper is structured as follows. Section 2 provides a brief literature review of studies regarding the COVID-19 pandemic, using trend and time-series analysis of road fatalities, clustering, and data mining approaches. Section 3 briefly describes the data, preprocessing, and analytical procedures. Section 4 states the results of the study, such as descriptive patterns, cluster formation, and statistical findings concerning COVID-19 effects and fatality trends. Section 5 includes the discussion of the results and the implications of them compared to the Safe System approach. Finally, Section 6 provides the conclusions of the paper and offers directions for future research and policy implications.

## 2. Literature Review

### 2.1 Safe System Framework and Regional Safety Context

The Safe System approach has become the basis for the modern road safety policy, as it acknowledges that while human error on the road is inevitable, death or serious injury resulting from a crash is not. It focuses on the prevention of injuries, rather than solely on the causes of crashes (OECD/ITF, 2020; Stipdonk et al., 2025). This approach recognizes the dynamic interaction between operating speeds, vehicles, road infrastructure, and road-user behavior in a holistic and integrated way. National and regional reports conducted for Greece observed that the complex urban environment of Attica, with the circulation of different modes, and high motorcycle usage, is a challenging case study that could benefit from a targeted data-driven study (NTUA Road Safety Observatory, 2025a; NTUA Road Safety Observatory, 2025b; Yannis et al., 2023).

### 2.2 Descriptive and Trend Analysis

For the investigation of road fatality trends, descriptive and statistical modelling approaches are being used to detect temporal changes and emerging risk factors. The study of Yousefzadeh-Chabok et al. (2016) provides a methodological framework for analyzing long-term variations and potential turning points in safety performance by including linear regressions, ARIMA, and generalized additive models. The study of Folla et al. (2023) gave a more regional perspective by investigating the effects of transport and socioeconomic characteristics on road safety in 13 different regions of Greece, by applying cluster analysis and developing mixed linear models. Same Sekadakis et al. (2021) to investigate the impact of the COVID-19 pandemic on road traffic collisions, fatalities, and injuries used time series analyses, such as three Seasonal Autoregressive Integrated Moving Average time series models.

### 2.3 Clustering Methods for Road Accident Data

Recent studies have demonstrated the benefits of cluster analysis in mitigating unobserved heterogeneity in traffic crash data. The **hierarchical clustering** method is applied in driver classification to explore the contributing factors related to driver risk (Parikh, 2021). They applied **hierarchical agglomerative cluster** analysis to characterize similarities in a group of crash information variables and evaluated road safety by considering driver behavior and performance under psychological workload in complex environments. Additionally, Manasa et al., (2024) applied hierarchical and partitioning around medoids clustering algorithms to detect the factors causing road accidents. Hayashi et al., (2023) utilized a hierarchical cluster analysis of young drivers, suggesting that this method resulted in the successful identification of three distinct subgroups of drivers. Finally, Iamtrakul & Chayphong, (2025) applied a GIS-based spatio-temporal clustering analysis for road traffic accidents, highlighting the importance of analysing both the spatial and temporal dimensions of road traffic accidents.

### 2.4 COVID-19 and the Dynamics of Road Fatalities

The COVID-19 pandemic affected road safety as it impacted traffic volumes, travel behavior, and massively reduced overall mobility activity. Wegman & Katrakazas, (2021) compares road fatalities and fatality rates compared to the previous period, 2017-2019, observing lower fatalities due to less mobility. Additionally, Ungureanu et al., (2024) examined the impact of COVID-19 on victims of road traffic accidents and observed temporal and demographic shifts in fatal road traffic accidents during the pandemic and in the previous years. In summary, previous studies examine trends, pandemic impacts, different clustering methods, and spatial hotspot identification, but few of them combine descriptive analysis with clustering methods and pre-/post-significance testing and trend regression models for regional data analysis. The present

study addresses this gap by integrating multiple analytical methods to evaluate fatality dynamics in Attica.

### 3. Methodology

The data utilized in the current study were collected from the **NTUA Road Safety Observatory (NRSO)** and contain the number of road fatalities in the **Attica region**, Greece, during the period 2016–2022. The dataset includes the total number of road fatalities per year, as well as disaggregated data along several dimensions, including road user type, age, gender, road type, geographical area, lighting conditions, number of vehicles involved, and weather conditions. For further analysis of the study, the data were converted into a **Long-format dataset** for consistency in the temporal and categorical analyses, with individual rows containing a combination of the category, year, and number of fatalities. Data preprocessing included the removal of aggregate rows, standardization of category labels, and consistency checks across years. The missing values were verified and imputed only when contextually valid. The conducted dataset was the base for all the analyses.

#### 3.2 Descriptive Analyses

Descriptive analytics was used to show how data points are distributed across time and categories. From the analysis, the fatalities per year, the demographic fatality trends, the number of fatalities based on different conditions, and the trends of fatalities by the road user category were calculated. The outputs of the analysis served as inputs for the following clustering and statistical model development. All analyses in this study are based on fatality counts. No exposure denominators (e.g. vehicle-km, population) were available; therefore, no fatality rates are calculated or compared.

#### 3.3 Hierarchical Cluster Analysis

Hierarchical **agglomerative clustering** using **Ward's linkage and Euclidean distance** was applied to identify structural patterns among fatality categories. All variables were standardized prior to analysis. Categories were treated as observations and years (2016–2022) as variables. The optimal cluster structure was determined through dendrogram inspection. The results were visualized using a dendrogram and a heatmap of standardized fatality values to illustrate similarities in temporal evolution.

#### 3.4 Pre-/Post- COVID-19 Comparison

For the comparison of pre- and post-COVID and to examine the effects of the COVID-19 pandemic on fatality patterns, the period was divided into two: pre-COVID (2016–2019) and post-COVID (2020–2022). The mean annual number of fatalities was calculated for each category for the two periods.

Then, a **two-sample t-test assuming unequal variances** was applied to evaluate whether the mean numbers of fatalities during the pre- and post-COVID periods were statistically significant. The categories that were characterized as **significantly influenced by the pandemic** had a **p-value <0.05**.

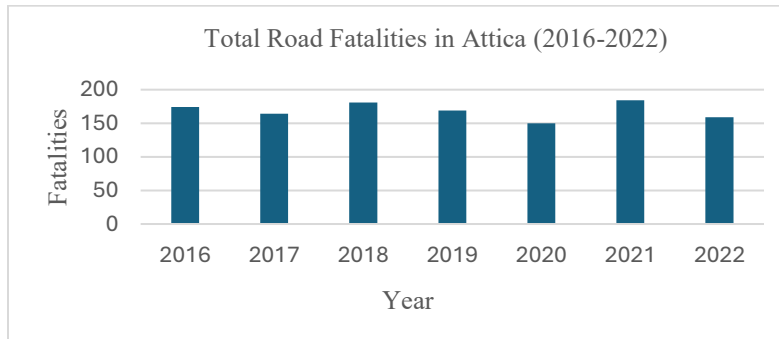
#### 3.5 Trend and Regression Analysis

The current study developed **simple linear regression models** for each fatality category to assess the fatality count changes over time required. The independent variable was **year**, and the dependent variable was represented by the **number of fatalities**. The direction of change became evident through the positive or negative values of the regression slope ( $\beta_1$ ), which also showed the strength of each trend through the coefficient of determination ( $R^2$ ). The interpretation of weak or unstable temporal patterns required categories to show low  $R^2$  values. The **trend regression plot** presented a visual representation of trend directions and intensities, which summarized the research findings. Most fatality types maintained steady patterns while their numbers decreased slightly, but the models explained the data poorly because of their low  $R^2$  values.

## 4. Results

### 4.1 Descriptive Statistics

From the descriptive analysis in the region of Attica for the period 2016–2022, temporal and categorical variations were conducted. Firstly, as shown in **Figure 1**, annual total fatalities ranged from 150 to 184 during 2016–2022, with the lowest count recorded in 2020 and a peak in 2021 following the easing of pandemic-related mobility restrictions. This indicates a reduction in fatalities when the pandemic started and a recovery once mobility restrictions were lifted.



**Figure 1:** True annual total road fatalities in Attica (2016–2022)

Furthermore, **Table 1** presents the descriptive statistics for each category. It is observed that **men drivers killed**, **motorcyclists killed**, and **pedestrians killed** are the highest mean counts, while **cyclists killed** and **children killed** have the lowest mean counts. **Variation** had high values for cyclists killed, and when it rained, which represents instability over the years. Also, fatalities were mainly concentrated **inside built-up areas**, during night-time and daytime, due to their high mean values, which confirms the persistence of risk factors that are based on visibility, the type of area, and environmental factors.

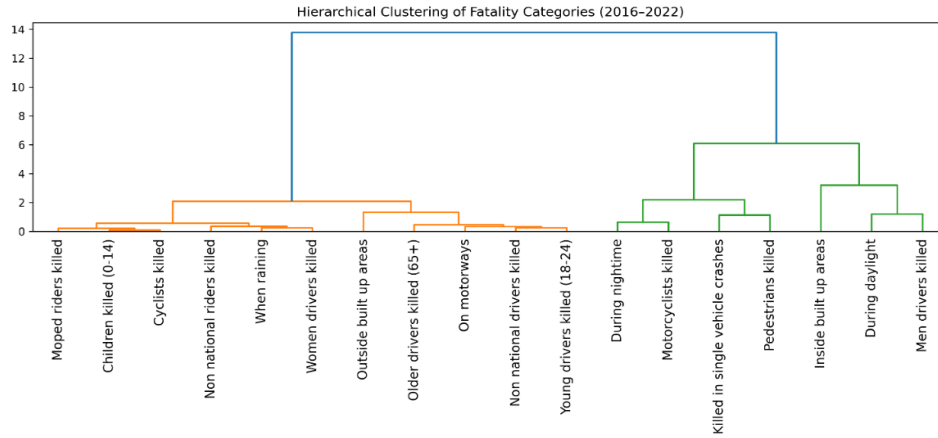
**Table 1.** Descriptive statistics of road fatalities by category, Attica (2016–2022).

Category	mean	std	min	max	variation_ %
<b>Children killed (0-14)</b>	1.71	0.95	0.00	3.00	55.49
<b>Cyclists killed</b>	2.14	1.21	1.00	4.00	56.70
<b>Moped riders killed</b>	3.00	2.58	0.00	7.00	86.07
<b>Women drivers killed</b>	5.00	1.91	2.00	8.00	38.30
<b>When raining</b>	6.57	3.82	2.00	12.00	58.18
<b>Non-national riders killed</b>	8.57	2.99	4.00	13.00	34.91
<b>Non-national drivers killed</b>	11.86	2.97	8.00	16.00	25.03
<b>On motorways</b>	14.71	4.54	10.00	22.00	30.82
<b>Young drivers killed (18-24)</b>	14.71	3.25	11.00	19.00	22.10
<b>Older drivers killed (65+)</b>	17.86	5.21	13.00	26.00	29.18
<b>Outside built-up areas</b>	29.71	7.25	16.00	37.00	24.40
<b>Pedestrians killed</b>	44.43	11.94	30.00	63.00	26.88
<b>Killed in single-vehicle crashes</b>	55.00	6.68	46.00	64.00	12.15
<b>During nighttime</b>	72.29	8.92	62.00	83.00	12.34
<b>Motorcyclists killed</b>	72.86	4.34	67.00	79.00	5.95
<b>During daylight</b>	89.57	7.32	80.00	98.00	8.18
<b>Men drivers killed</b>	104.86	4.98	99.00	112.00	4.75
<b>Inside built-up areas</b>	139.00	9.88	127.00	153.00	7.11
<b>Total road fatalities</b>	168.71	12.11	150.00	184.00	7.18

#### 4.2 Cluster Analysis

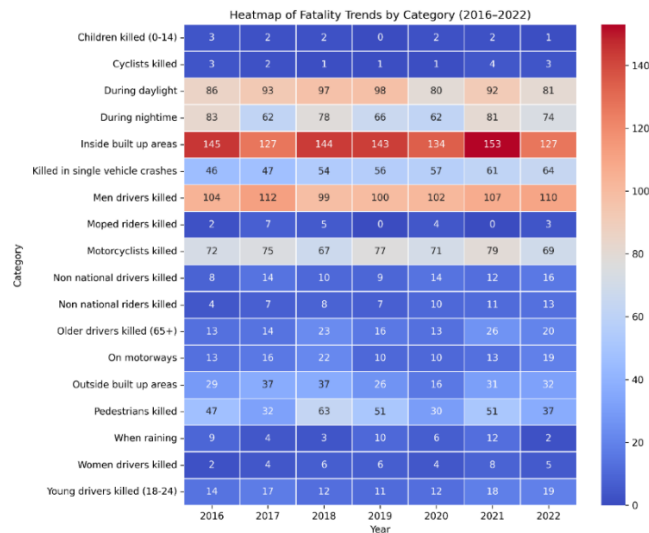
To investigate the structural patterns between the categories of the dataset, hierarchical clustering was applied. **Figure 2** represents a dendrogram that reveals the three main clusters of behavior, using Ward's linkage and standardized values.

- **Cluster 1 (Low-volume / volatile)** includes categories with smaller and more variable fatality counts: children killed, cyclists killed, non-national drivers killed, women drivers killed, and rain conditions.
- **Cluster 2 (Vulnerable users and behavioural risk)** groups motorcyclists killed, pedestrians killed, single-vehicle crashes, and nighttime crashes, reflecting sensitivity to exposure and behavioural factors.
- **Cluster 3 (High-volume / systemic risk)** captures the structurally dominant categories: men drivers killed, inside built-up areas, and daylight crashes.



**Figure 2.** Hierarchical clustering dendrogram of fatality categories (Ward’s method).

Furthermore, from the cluster analysis, a heatmap of **standardized fatality values (Figure 3)** was produced to illustrate the annual evolution of fatality counts per category. The warmer tones (red, orange, etc.) that correspond to cluster 1 reflect persistent high-risk patterns, in contrast to cooler tones (blue, white, etc.) that correspond to cluster 2, which reflect decline or stability.



**Figure 3.** Heatmap of standardized fatality values by category and year (2016–2022). Colours reflect standardized (z-score) fatality counts, not correlations. Warmer tones (red/orange) indicate above-average counts; cooler tones (blue/white) indicate below-average counts.

### 4.3 Pre-/Post- COVID Comparison

For the pre- and post-COVID comparison and for the investigation of the effects of the pandemic on the fatality counts, the data were subdivided into the pre-COVID (2016-2019) and post-COVID (2020-2022) periods. Specifically, two sample t-tests were applied to evaluate the difference in mean counts between the categories. Given the small number of annual observations in each period (four pre-COVID years: 2016–2019, and three post-COVID years: 2020–2022), the following results should be interpreted as exploratory evidence of possible pandemic-related shifts rather than definitive causal findings. In **Table 3**, it is observed that **non-national riders** experienced a **+74%** increase in the post-COVID period, and **single-vehicle crashes** increased by **+19%**. The results were statistically significant ( $p < 0.05$ ) for two categories: single-vehicle crashes ( $p = 0.03$ ) and children killed ( $p = 0.01$ ). Non-national riders showed a large descriptive increase of **+74%** in the post-COVID period but this did not reach statistical significance ( $p = 0.99$ ), likely due to the small sample size and high variability across years. These findings should be treated as exploratory, given the limited number of observations per period.

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**Table 3.** Results of pre-/post-COVID comparison of mean fatalities by category.

Category	Pre_COVID_Mean	Post_COVID_Mean	Change	% Change	p-value (t-test)
Children killed (0-14)	1.75	1.67	-0.08	-4.76	0.01
Cyclists killed	1.75	2.67	0.92	52.38	0.43
During daylight	93.50	84.33	-9.17	-9.80	0.09
During nighttime	72.25	72.33	0.08	0.12	0.49
Inside built-up areas	139.75	138.00	-1.75	-1.25	0.34
Killed in single-vehicle crashes	50.75	60.67	9.92	19.54	0.03
Men drivers killed	103.75	106.33	2.58	2.49	0.52
Moped riders killed	3.50	2.33	-1.17	-33.33	0.96
Motorcyclists killed	72.75	73.00	0.25	0.34	0.52
Non-national drivers killed	10.25	14.00	3.75	36.59	0.95
Non-national riders killed	6.50	11.33	4.83	74.36	0.99
Older drivers killed (65+)	16.50	19.67	3.17	19.19	0.86
On motorways	15.25	14.00	-1.25	-8.20	0.54
Outside built-up areas	32.25	26.33	-5.92	-18.35	0.91
Pedestrians killed	48.25	39.33	-8.92	-18.48	0.75
Total road fatalities	172.00	164.33	-7.67	-4.46	0.13
When raining	6.50	6.67	0.17	2.56	0.39
Women drivers killed	4.50	5.67	1.17	25.93	0.36
Young drivers killed (18-24)	13.50	16.33	2.83	20.99	0.58

*4.4 Regression and Trend Analysis*

For the evaluation of fatality count changes over time, a **simple linear regression** was applied to each category, with year set as the independent variable and fatalities as the dependent variable.

Presented in **Table 4**, most categories show small positive or near-zero slopes, which indicates stability in fatality counts during the period 2016-2022.

**Table 4.** Linear regression results for fatality trends by category (2016–2022).

Category	Slope ( $\beta$ )	R <sup>2</sup>	Trend
Total road fatalities	1.5	0.18	Increasing (weak)
Pedestrians	-1.75	0.32	Decreasing
Motorcyclists	-0.25	0.05	Stable
Moped riders	0.10	0.02	Stable
Cyclists	0.25	0.04	Stable
Young drivers (18–24)	0.60	0.25	Increasing
Older drivers (65+)	1.20	0.41	Increasing
Children (0–14)	-0.15	0.10	Stable
Men drivers	0.75	0.30	Increasing
Women drivers	0.25	0.18	Increasing
Non-national drivers	1.10	0.38	Increasing
Non-national riders	1.25	0.47	Increasing
Inside built-up areas	1.75	0.35	Increasing
Outside built-up areas	-0.40	0.12	Stable
On motorways	0.55	0.29	Increasing

Category	Slope ( $\beta$ )	R <sup>2</sup>	Trend
When raining	−0.20	0.08	Stable
During daylight	−0.60	0.26	Decreasing
During nighttime	0.50	0.31	Increasing
Single-vehicle crashes	1.00	0.42	Increasing

#### 4.5 Summary of Findings

By combining descriptive, cluster, and regression analyses, **Table 5** provides an integrated overview of fatality patterns across identified risk domains. The synthesis highlights how structural exposure, vulnerability, and contextual conditions interact with pandemic-related impacts and temporal trends.

**Table 5.** Summary of fatality characteristics by cluster, COVID impacts, and trend slope.

Cluster	Representative Categories	COVID Impact (Mean Change)	Significant ( $p < 0.05$ )?	Trend Type	Overall Interpretation
<b>Cluster 1: Low volume / volatile</b>	Children killed, Cyclists, Non-national drivers, Women drivers, Rain conditions	Minor or no change	No	Stable	Small but variable numbers; limited contribution to totals.
<b>Cluster 2: Vulnerable users &amp; behavioral risk</b>	Motorcyclists, Pedestrians, Single-vehicle crashes, Nighttime crashes	Moderate to strong increases	Yes (for single-vehicle crashes)	Increasing or fluctuating	Sensitive to exposure and behavioral changes; key COVID-affected group.
<b>Cluster 3: High-volume / systemic risk</b>	Men drivers, Built-up areas, Daylight crashes	Minimal mean change	No	Slightly increasing	Consistently dominant categories form structural core of fatality patterns.

The research shows that traffic fatality numbers have not risen dramatically, but risk patterns in Attica have changed since COVID-19, so continuous monitoring of **vulnerable road users** and **non-national populations** and behavioral crash types remains essential.

#### 5. Discussion

Although overall fatality levels in Attica remained relatively stable during 2016–2022, structural risk patterns shifted following the COVID-19 pandemic. The temporary reduction in 2020 and rebound in 2021 are consistent with international evidence linking mobility restrictions to short-term safety improvements. VRUs, specifically motorcyclists and pedestrians, remain the structural core of urban fatality risk. The statistically significant increase in single-vehicle crashes ( $p=0.03$ ) and decrease in children killed ( $p=0.01$ ) during the post-COVID period may be consistent with changes in travel behaviour and exposure patterns, though causal attribution is not possible from these data alone. These results are best treated as hypotheses to be tested with mobility and exposure data in future work. Non-national riders showed a large descriptive increase (+74%) that warrants continued monitoring, despite not reaching statistical significance ( $p=0.99$ ).

The trend regression shows that fatality trends are weakly linear, suggesting that developments are driven by a complex interaction of factors rather than a single long-term trajectory. The clustering analysis identifies groups with similar temporal behaviour and separates high-volume systemic risks from less frequent and more volatile categories.

From a Safe System perspective, these findings support the relevance of prioritising vulnerable road user management, behavioural risk management, and exposure management in urban settings. The persistence of motorcycle and nighttime risks, coupled with observed structural shifts post-COVID, suggests the need for flexible traffic monitoring and responsive policies to achieve road safety goals in Greece by 2030.

#### 6. Conclusions

This study examined road fatalities in the Attica region during 2016–2022 using descriptive analytics, hierarchical clustering, regression analysis, and pre-/post-COVID comparisons. The findings point to two persistent risk patterns:

motorcyclists, pedestrians, and urban road users consistently account for the highest fatality counts, while single-vehicle crashes showed a statistically significant increase in the post-COVID period ( $p=0.03$ ).

Continuous monitoring of specific population groups and crash conditions is essential, as aggregate fatality totals alone do not capture subgroup dynamics. These findings are consistent with Safe System principles and suggest that policymakers consider targeted safety measures for high-risk road users, with particular attention to nighttime urban conditions and post-COVID behavioral shifts. Combining clustering methods with statistical testing and trend evaluation provides useful knowledge about how fatality patterns distribute and evolve over time. Future work should incorporate spatial exposure data, such as traffic volume, population density, and land use, to support customized regional action plans aligned with Greece's 2030 Road Safety Strategy.

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