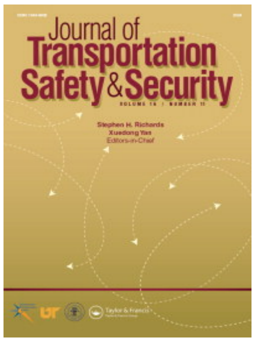

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ABSTRACT

Previous research has demonstrated that crashes involving motorcycles and fixed objects often result in severe injuries. However, there is a scarcity of stand-alone studies examining the contributing factors related to this specific type of crash. This study sought to address this gap by analyzing a comprehensive dataset comprising 1,198 crash observations involving motorcycles and fixed objects over a 5-year period (2016–2020) in Massachusetts. By understanding the contributing factors more comprehensively, this study aims to facilitate targeted interventions to mitigate the severity of crashes involving motorcycles and fixed objects, ultimately fostering a safer road environment. Through data conflation, various factors pertaining to driver demographics, driver actions, road features, traffic characteristics, weather conditions, and lighting conditions were considered for this analysis. A novel approach called cluster correspondence analysis (CCA) was employed to uncover underlying patterns associated with these crashes. The insights derived using this unique method will significantly contribute to the limited literature on this topic, providing valuable information for road users and stakeholders to implement policies that enhance overall road safety.

KEYWORDS

Fixed objects; motorcycle safety; traffic crashes; cluster correspondence analysis

1. Introduction

Motorcycles are used worldwide because they offer more convenience, agility, and freedom than cars. However, this fast two- or three-wheeled mode of transport can also pose significant safety challenges as they do not provide any body of protection for its users. Compared to passenger cars, the fatality rates of motorcyclists were almost 24 times higher per vehicle mile

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traveled (NHTSA, 2022). However, despite the high crash fatalities associated with motorcycles, many keep using them as a mode of transportation.

Some previous studies investigated critical risk factors associated with different levels of injuries associated with motorcycle crashes. While some studies performed holistic studies on motorcycle crashes (Geedipally et al., 2011; Rezapour et al., 2021; Yousif et al., 2020), others investigated specific cases like motorcycle-car crashes (Magazzù et al., 2006; Maistros et al., 2014), motorcycle-bicycle (Haworth & Debnath, 2013) crashes, and motorcycle crashes at intersections (Haque et al., 2010; Pai, 2009). However, there have been limited studies regarding motorcyclist and fixed object crashes (Daniello & Gabler, 2011, 2012). Analyses involving collisions between motorcyclists and fixed objects used to be only a fraction of the broader studies involving motorcyclist crash studies (Pervez et al., 2022; Shaheed & Gkritza, 2014; Sivasankaran et al., 2021). The existing literature on motorcycle-fixed object crashes used methods like crash outcome data evaluation (Daniello & Gabler, 2012), single variable logistic regression (Bambach et al., 2011), odds ratios, and chi square tests (Tung et al., 2008) to examine factors influencing these crashes. Comparing these models with cluster correspondence analysis (CCA), CCA stands out for its advantages in providing unique insights. Using the novel CCA method, this study aimed to answer the following research questions:

- What are the main patterns and contributing factors associated with motorcycle crashes involving fixed objects?
- How can we use CCA to find new insights from the crash dataset and inform stakeholders to implement targeted policies and interventions to mitigate the number and injury severity of crashes involving fixed objects?

Using five years of crash (2016–2020) data from Massachusetts, this study examined the patterns of contributing factors associated with motorcyclist-fixed object crashes. By using only motorcyclist-fixed object-related crash data, factors including crash characteristics, driver characteristics, and road and traffic characteristics were analyzed. Identifying the patterns associated with these crashes will help policymakers and stakeholders develop policies and strategic interventions that will significantly reduce the number of fixed-object crashes among motorcyclists.

2. Literature review

Motorcyclists face significantly higher rates of injury and fatalities due to the absence of vehicular structure protection. In a study conducted by

Daniello and Gabler (2011), the fatality risk associated with motorcycle crashes involving roadside objects was analyzed, and it was found that these crashes often involve more than a single impact event. The study also found that collisions with roadside objects carried a higher risk of fatality than collisions with the ground or another motor vehicle. This underscores the finding that for motorcyclists, collisions with fixed objects are more perilous than ground collisions.

A considerable body of research has been dedicated to examining motorcycle crashes involving fixed objects, including but not limited to roadside barriers, guardrail systems, posts, and poles. Bambach and Grzebieta (2014) revealed through statistical analysis that posts and poles pose a greater risk to motorcyclists compared to roadside barriers, regardless of barrier type or crashworthiness of the motorcycle. Hence, it is suggested to employ barriers in front of fixed objects to enhance motorcyclist safety. Additionally, improperly designed barriers present a higher hazard to motorcyclists in comparison to vehicle occupants. Motorcyclist-barrier crashes resulted in severe or fatal injuries in half of the cases, whereas such outcomes were seen only in 13% of the vehicle occupant cases. This brings into focus the need for better roadside barrier designs, particularly in motorcycle crash-prone areas. The study also reviewed strategies for protecting motorcyclists from roadside barrier crashes, focusing primarily on steel W-beam barriers, a significant contributor to motorcycle casualties and fatalities. Rub-rails were found to be the most effective in reducing potential injuries when impacting W-beam barriers, while concrete barriers also showed safety improvements, particularly in sliding crashes.

Opiela et al. (2010) overviewed roadway hazards contributing to the severity of single motorcycle crashes in the US. W-beam steel barriers were found to be disproportionately represented in fatal motorcycle crashes, posing a particular threat to riders. Wire-rope barriers, in contrast, significantly reduced vehicle-related fatalities in Europe and the USA. Tjahjono (2016) highlighted four types of accidents often resulting in motorcycles being forced off the road: loss of control, sideswiping, broadsiding, and collisions with fixed objects, including animals. To mitigate these risks, the study proposed the installation of infrastructure like hard seal shoulders and appropriate guardrails to prevent motorcyclists from rolling over or being forced off the road. Reflective delineators and chevron alignment markers were suggested to enhance night safety, especially on tight bends. Moreover, safety measures, such as helmet usage were advocated to reduce the severity of crashes.

Several studies have implied roadside safety barriers are a significant factor affecting severe injuries and fatalities among motorcyclists. Traditionally, these barriers were designed with the safety of enclosed vehicle occupants in mind, often neglecting the unique risks faced by motorcyclists. Gabler (2007) examined this issue, finding that motorcyclists constituted a disproportionate number of fatalities from guardrail collisions despite making up only 2% of the vehicle fleet. The study stressed that this is a growing issue, further highlighting the need for motorcycle-friendly guardrail designs. To gain better insights into the interaction between motorcyclists and barriers during crashes, computer simulations were proposed by Mongiardini et al. (2017). These simulations aimed to develop a detailed model of a sport-touring motorcycle and its impacts on different types of roadside safety barriers. Schulz et al. (2018) used a similar approach to assist with the design of roadside safety hardware, introducing a new motorcycle-friendly barrier concept to prevent severe injuries during upright impacts against concrete barriers.

The construction of exclusive motorcycle lanes was also explored as a potential measure to reduce fatalities. Prior research emphasized the risk of roadside object crashes and excessive speed in such lanes, but there was limited exploration of same-direction crashes and the impact of lane geometry and roadside configurations. Ibrahim et al. (2018) used naturalistic riding data to study the effects of these factors on overtaking speed, lateral position, and comfortable overtaking likelihood. Guardrails were identified as the most struck object in exclusive motorcycle lanes and found to contribute to serious injuries and fatalities, calling for further research on guardrail design systems and material types. Tung et al. (2008) analyzed crash data from Malaysia's two longest motorcycle lanes. Over 4.5 years, 107 crashes involving motorcycles and roadside objects were recorded, with guardrails being the most frequently struck object. The analysis showed that while narrow surface objects had a higher fatality rate, guardrails were involved in 23.5% of all fatal crashes and were 1.7 times more likely to cause serious injuries than crashes without objects. This supports the use of guardrails as a safety measure on motorcycle lanes. Research by Jama et al. (2011) analyzed 77 motorcycle fatalities involving roadside barriers in Australia and New Zealand. These crashes typically involved single-vehicle incidents and young male riders, occurring predominantly during daylight hours on clear, dry days. Speeding and drunk driving were significant contributors to these fatalities.

2.1. Research gap and study contribution

Motorcyclists are at a significantly higher risk of injury and fatality in crashes due to the absence of vehicular protection, especially in crashes involving fixed objects, such as barriers, poles, and trees. Several studies have highlighted the danger posed by roadside objects, with collisions involving fixed objects being more perilous than those involving other vehicles or the ground (Daniello & Gabler, 2011). Previous research, such as that by Bambach and Grzebieta (2014), has identified specific roadside hazards, like posts and poles, as posing a heightened risk to motorcyclists. Although these studies have emphasized the need for better roadside barrier designs and the implementation of safety features like rub-rails, most of the research has focused on barriers and their interaction with motorcyclists. There is still a significant gap in understanding how other factors—such as road conditions, lighting, and driver behavior—contribute to motorcycle-fixed object crashes.

This study aims to address this gap by employing a novel approach using Cluster Correspondence Analysis (CCA) to explore the patterns of motorcycle-fixed object crashes. CCA, combined with a multi-level analysis, provides a new perspective on the factors influencing crash severity. By clustering crash data into distinct groups based on severity (fatal, injury, and property damage only), this study identifies unique patterns of risk factors associated with each cluster, such as road types, lighting conditions, and driver demographics. This approach goes beyond traditional analyses of fixed object crashes by identifying specific attributes within each cluster that can inform the need for motorcycle safety specific countermeasures. Through this methodology, the study contributes to the literature by offering insights into motorcycle-fixed object crashes and providing a basis for targeted road safety enhancement for motorcyclists.

3. Methodology

3.1. Data collection

The researchers collected motorcycle crash data for five years (2016–2020) from Massachusetts. In seven years, 1,198 motorcycle crashes in Massachusetts were identified (see Table 1 and Figure 1). The data was filtered by selecting a wide list of roadside fixed objects. Massachusetts crash data provides severity types in three categories: fatal (K), injury (ABC), and property damage only (PDO; represented by O). Over the five-year period from 2016 to 2020, motorcycle-related fixed object crashes showed varying trends. Fatal crashes experienced a slight decrease, with a percentage decrease of 7.89% from 13 in 2016 to 12 in 2020. However, injury crashes

Table 1. Yearly motorcycle fixed object crashes by injury types.

Year	Fatal	Injury	PDO	Unknown	Yearly total
2016	13	205	37	15	270
2017	18	188	31	4	241
2018	16	175	26	7	224
2019	17	157	23	7	204
2020	12	210	26	11	259
Grand total	76	935	143	44	1198

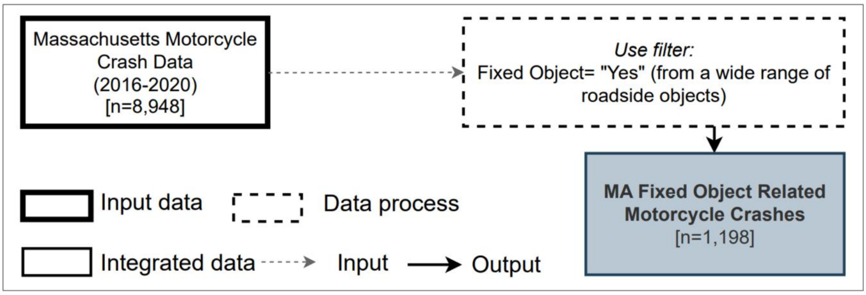

Figure 1. Flowchart of data preparation.

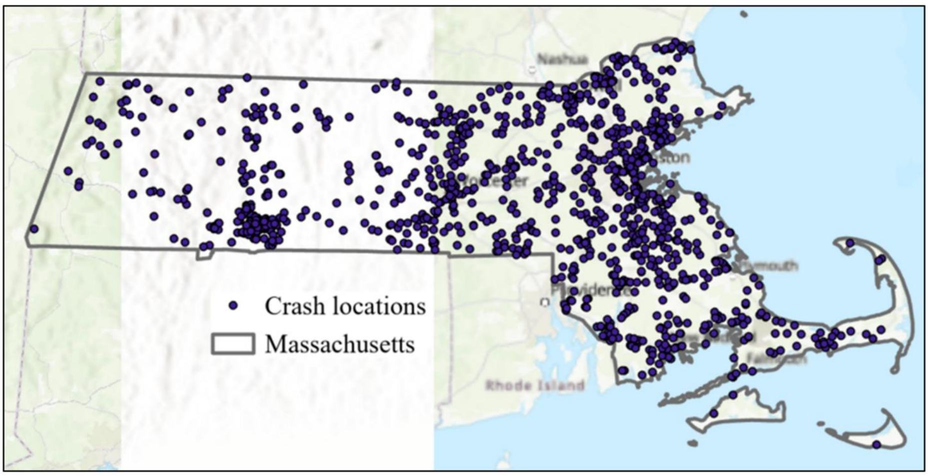

Figure 2. Locations of fixed object motorcycle crashes (2016–2020) in Massachusetts.

saw a modest increase of 2.15%, rising from 205 in 2016 to 210 in 2020. PDO crashes declined by 22.97%, decreasing from 37 in 2016 to 26 in 2020. The number of crashes with an unknown outcome decreased by 70.45%, dropping from 15 in 2016 to 11 in 2020. When considering all categories combined, the overall total of motorcycle fixed object crashes showed a 7.46% increase, rising from 270 in 2016 to 259 in 2020. Analyzing these percentage changes can help identify areas where improvements and safety measures are needed to reduce motorcycle accidents and enhance road safety.

Figure 1 illustrates the process of filtering Massachusetts motorcycle crash data from 2016 to 2020. The initial dataset contains 8,948 crash observations. The data is processed by applying a filter that selects only crashes involving a fixed object, identified from a wide range of roadside objects. After applying this filter, the resulting dataset includes 1,198 motorcycle crashes specifically related to fixed objects.

Figure 2 shows the locations of fixed object-related motorcycle crashes that occurred in Massachusetts from 2014 to 2020. Urban and city center locations show a higher density of motorcycle crashes.

3.2. Cluster corresponding analysis (CCA)

CCA, an unsupervised data mining method, was chosen for this study as it offers several advantages over traditional regression models, which typically focus on the average effects of risk factors across an entire population. One of the main limitations of regression models is that they often overlook the presence of subgroups with distinct risk profiles, potentially leading to interventions that are not well-investigated. CCA, on the other hand, allows for the identification of subgroups with heterogeneous risk profiles, offering the understanding of the interactions between various factors that contribute to motorcycle-fixed object crashes. Unlike regression models, CCA does not impose assumptions on the subgroups or risk factor distributions, allowing the data to identify natural groupings based on patterns and associations. This method is particularly valuable in capturing the complexity of real-world crash data, where risk factors can interact in various ways, and their effects may vary across different crash severity outcomes.

CCA is a statistical technique that combines the concepts of correspondence analysis (CA) and cluster analysis. CA is a method for analyzing categorical data that displays the relationships between variables and categories in a two-dimensional space. Cluster analysis is a method for grouping similar observations together. CCA extends CA by adding a clustering step. In CCA, the observations are first clustered based on their similarities. Then, the CA procedure is applied to the clustered data to display the relationships between the clusters and the variables. CCA can be used to identify clusters of observations that share similar characteristics. It can also be used to visualize the relationships between clusters and variables. CCA is a powerful tool for exploring categorical data and identifying patterns in the data. CCA is a relatively new technique, but it has been shown to be effective for a variety of applications. The algorithm is based on the following two key steps (van de Velden et al., 2017):

- **Step 1:** The observations are first clustered based on their similarities. This is done by calculating a similarity measure between each pair of observations. The similarity measure can be based on the frequencies of the variables in the observations.
- **Step 2:** Once the observations are clustered, the CA procedure is applied to the clustered data. This results in a two-dimensional space in which the clusters are represented by points. The variables are also represented by points in the space. The distances between the points in the space reflect the relationships between the clusters and the variables.

Given a normal data matrix $\boldsymbol{X}$ with n observations containing q categorical variables, the first step involves developing a new matrix, $\boldsymbol{Z}$, named as a super indicator matrix. This matrix, $\boldsymbol{Z}$, is generated through a one-hot encoding process that transforms each categorical variable into a binary matrix. To consider the relationship between clusters and categorical variables, a $K \times p_j$ contingency matrix $\boldsymbol{F}$ can be constructed by cross tabulating the indicator matrix and the membership matrix $\boldsymbol{F} = \boldsymbol{Z}_{\boldsymbol{K}}^{\top}\boldsymbol{Z}$. The contingency matrix F is first subjected to CA. This aims to optimize the scaling values, which are used to determine the importance of the different categories, for clusters and categories, so that the inter-group variances are maximized. Under optimal conditions, the clusters will effectively separate the data based on the categorical variables. This will reveal valuable insights and patterns. The clusters can reveal valuable insights and patterns in the data (Ashifur Rahman et al., 2022). For example, the clusters may be able to identify different clusters of key influential factors associated with fixed object-related motorcycle crashes.

4. Results

CCA was used to find clusters associated with motorcycle-fixed object crash data using the "clustrd" function in the R software package (Markos et al., 2022). The CCA method encompasses the use of the MCA K-means approach and the Average Silhouette Width (ASW) criterion to find clustering solutions, separate data into clusters, and choose the optimal number of clusters. A range of clusters, from 2 to 10, and several dimensions, from 1 to 9, were initially specified. After several runs, the model chose three clusters and two dimensions as the best solution for the fatal, injury, and PDO datasets, as shown in Table 2. The clustering process utilized the MCA K-means approach, which is appropriate for categorical data, such as the crash factors used in this study. The method works by reducing the multidimensional categorical data into principal dimensions, which allows for easier visualization and interpretation of relationships within the data. In this case, two dimensions were selected because they captured the most variability in the dataset, making it easier to visualize how crash factors related to different clusters. The number and variables associated with each cluster can also be visualized using the biplots generated for each dataset

Table 2. Centroids and size of the clusters.

	Fatal			Injury			PDO		
Cluster number	Dim 1	Dim 2	Within cluster sum of squares	Dim 1	Dim 2	Within cluster sum of squares	Dim 1	Dim 2	Within cluster sum of squares
Cluster 1	0.0347	0.0214	0.0496	−0.0025	−0.0115	0.0348	0.0149	0.0137	0.0448
Cluster 2	−0.0669	−0.1903	0.0211	−0.0183	0.0422	0.0446	−0.0282	−0.1326	0.0461
Cluster 3	−0.2895	0.1192	0.0126	0.0919	0.0222	0.0146	−0.225	0.0595	0.0045

Dim: dimension or axis.

(i.e. fatal, injury, and PDO). As shown in Figures 3, 5, and 7, one can see that the centroids of cluster 1 and cluster 2 in each of the biplots were closer to the origin of the biplots, indicating that features within these two clusters are more representative of the entire data sets.

To better understand the associations between the variables in each dataset, bar plots showing the top 20 variables with the highest standardized residuals for each dataset are shown in Figures 4, 6, and 8. This same approach was used in previous studies (Das et al., 2021, 2022; Tamakloe et al., 2023). For every bar plot generated, the length of the bar indicates the dominance of that variable in the cluster. In addition, the variables with positive residuals (bars moving from left to right from the center) have above-average frequencies within the cluster. The bar plot results for each dataset are discussed in the section below.

4.1. Fatal crashes

To begin with crashes that were fatal, over 90% of the fatal crash data were categorized as Cluster 1 (C1) or Cluster 2 (C2; see Figure 3). The bar plots revealed that crashes involving fixed objects (the first harmful event) on two-way undivided road without medians, right and left shoulders, and speed limit <30 mph contributed to about 80% of fatal crashes. For the second cluster, different variables showed dominance in the dataset as compared to the first cluster. Crashes involving barriers/positive barriers on one-way roads and two-way divided roads with speed limits equal to or >50 mph in the presence of right and left shoulders formed about 13.2% of the fatal crash dataset. For the remaining 6.6% of the fatal crash dataset (Cluster 3; C3), there was a strong association between variables like speed limit >50 mph, one-way roads, two-way divided roads, and collision with barriers as also seen in cluster 2. However, the crashes in this cluster are

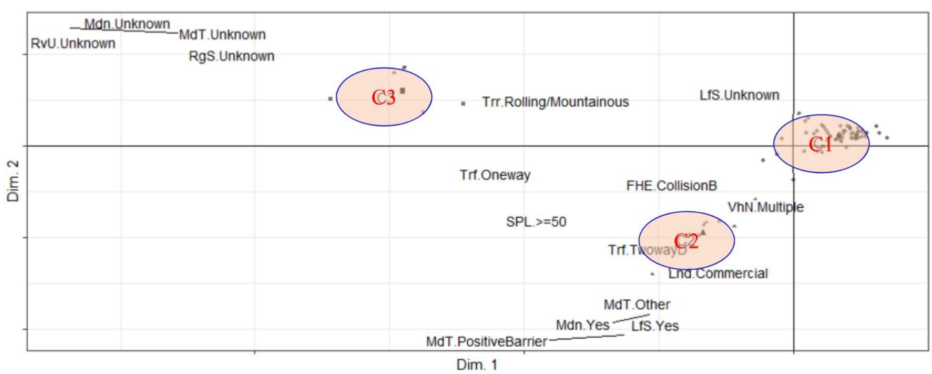

Figure 3. Correspondence analysis plot in fatal crashes.

also associated with rolling/mountainous terrains and dark unlighted roadways.

4.1.1. Cluster 1 (C1)—Fatal crashes occurred on two-way undivided low speed road without a median or shoulder and with first harmful event as collision with other fixed objects

In C1, the two sides of the cluster represent positive and negative standard residuals, indicating the presence or absence of specific variables within the group. When a variable has a positive residual, it means that it is well-represented in the cluster, while a negative residual suggests that the variable is less common in the cluster. The right-hand side of the cluster displays a cohesive group of categories that exhibit strong associations with each other. Notably, the highest bar on the positive side represents a non-median road, indicating its predominant presence within this cluster (see Figure 4). Prominent representations in Cluster C1 also include incidents where a two-way undivided road is involved, with the first harmful event a collision with other fixed objects, occurring at a speed of <30 mph, and lacking both a left shoulder and right shoulder. Such roads are most likely in local neighborhoods, rural areas, or some urban streets. Many other studies have also shown that safety barriers are associated with fewer motorcycle crashes, fatalities, and serious injuries compared to other types of medians (Cassell et al., 2006; Gibson & Benatatos, 2000).

4.1.2. Cluster 2 (C2)—Fatal crashes occurred on roads with positive barrier median, both-side shoulders, two-way divided traffic, speed limit above 50 mph, commercial location, and involving multiple vehicles

Within C2 of the fixed object collision motorcycle crash data, the highest association, represented by the highest bar on the right side of the chart (see Figure 4), is with median presence. This association involves roads with a positive barrier median, shoulders on both sides, two-way divided traffic, speed limits higher than 50 mph, commercial areas, and the first harmful event being a collision involving multiple vehicles. Such roads usually belong to major highways or expressways, where high-speed traffic is common due to their design and purpose. These roads are often found in urban areas with a significant volume of commercial activities and multiple lanes to accommodate heavy traffic flow. This finding was consistent with previous studies suggesting that a motorcyclist was more likely to be killed or severely injured in a traffic crash that occurred on a major road as compared with a local road (Eustace et al., 2011; Savolainen & Mannering, 2007). The main reason may be because of both the high travel speeds and traffic volumes on major roads.

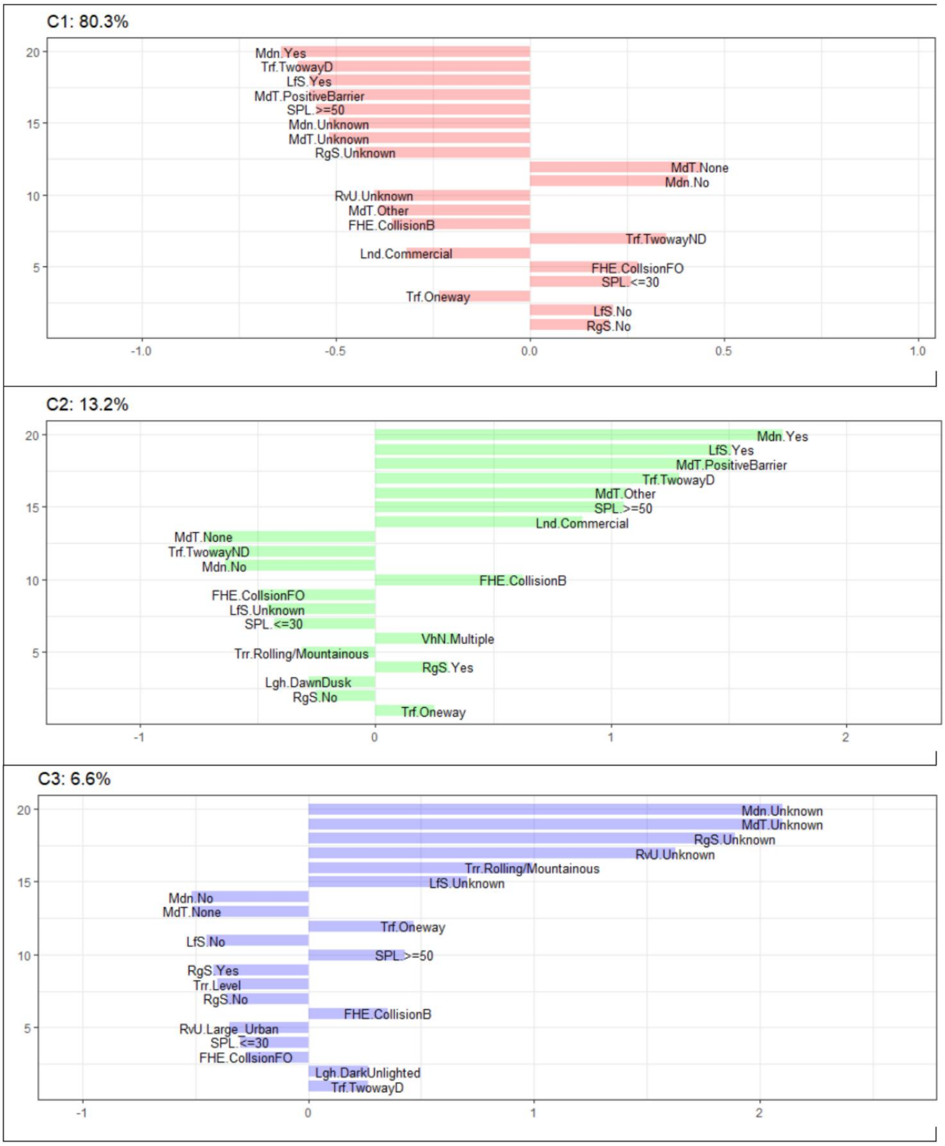

Figure 4. Clusters in fatal crashes.

4.1.3. Cluster 3 (C3)—Fatal crashes occurred unknown median type, unknown shoulder type, unidentified land use, rolling/mountainous terrain, involving multiple vehicles, one-way traffic, speed limit above 50 mph, and collision with a barrier as the first harmful event in dark-unlighted conditions

In the fixed object collision motorcycle crash data for C3, the most prominent association, represented by the tallest bar on the right side of Figure 4, is linked to the unknown presence of a median. This correlation pertains to roads with unspecified median type, unknown shoulder type, unidentified land use, located in rolling/mountainous terrain, involving multiple vehicles, featuring one-way traffic, and having a speed limit of >50 mph. Additionally, the first harmful event is identified as a collision with a barrier, occurring in dark-unlighted conditions. This analysis brought to light a significant portion of the dataset containing missing information, particularly concerning the unrecorded details about both shoulders and medians for crashes in this cluster. However, it was observed that fatal crashes within this cluster mostly occurred in mountainous terrain, involved one-way traffic, took place in dark-lighted conditions, and had speeds exceeding 50 mph. These types of roads are often found in rural or less densely populated areas, where terrain features, such as mountains or hills are more prevalent. They may be part of regional highways or major roads that connect different locations and allow for higher travel speeds. Additionally, roads with one-way traffic are commonly implemented in certain areas to control traffic flow and improve safety. In the Shaheed et al. (n.d.) study, the analysis of crash severity outcomes based on light conditions revealed significantly higher rates of fatal crashes during dark conditions compared to daylight, and the same pattern was observed for possible/unknown and PDO crashes.

4.2. Injury crashes

Comparing the clusters for injury crashes with fatal crashes, a similar trend of the variable type and their distributions was observed (see Figure 5). C1, constituting about 76% of the entire dataset, involves collision with fixed objects on two ways undivided rural roads without left/right shoulders and a speed limit of ≤30 mph. On the other hand, C2, forming about 18% of the dataset, revealed that crashes involving hitting barriers on one-way or two-way divided roadways in commercial areas with speed limits ≥50 mph were likely to result in injuries. C3 demonstrated strong associations between crashes occurring on mountainous/rolling terrains with dark conditions and no lighting.

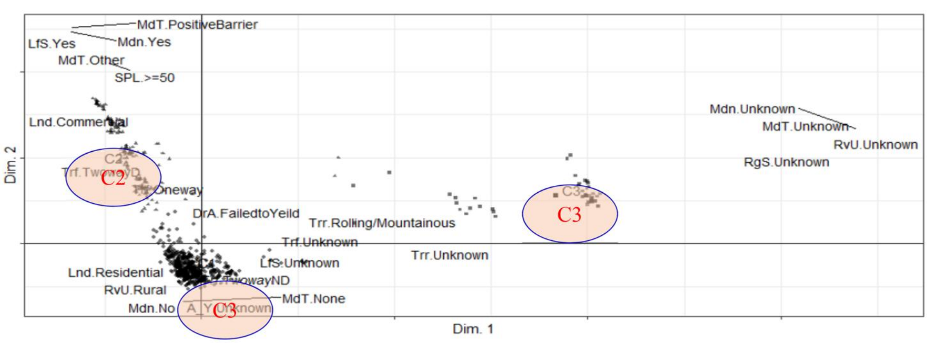

Figure 5. Correspondence analysis plot in injury crashes.

4.2.1. Cluster 1 (C1)—Injury crashes occurred on roads with no median, two-way undivided, no right shoulder, rural setting, no left shoulder, and speed limit <30 mph

In the fixed object collision motorcycle injury crash data for C1, the most notable association, depicted by the tallest bar on the right side of Figure 6, is linked to roads without a median. This correlation involves two-way undivided roads with no right shoulder, situated in rural areas, lacking a left shoulder, and with a speed limit of <30 mph. The first harmful event in these crashes is identified as collision with other fixed objects. The types

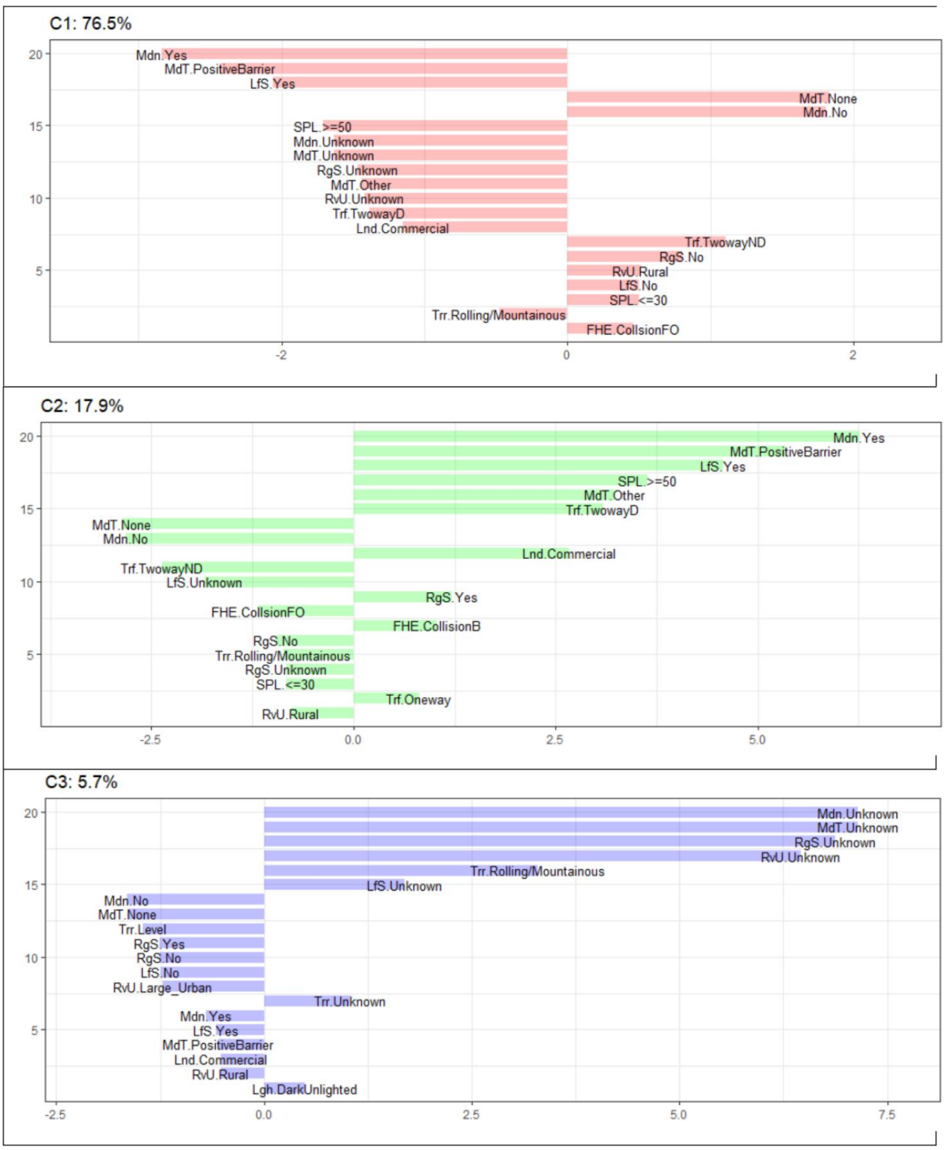

Figure 6. Clusters in injury crashes.

of roads are typically found in rural or less densely populated areas. In Francis's study on high-risk locations for motorcycle-related injuries (Francis et al., 2021), similar clusters were identified, which were associated with more fatal or severe injuries. These clusters were characterized by a high representation of trunk roads, undivided two-way roads, a mixture of road users, and the presence of commercial and residential areas.

4.2.2. Cluster 2 (C2)—Injury crashes occurred on roads with positive barrier median, both-side shoulders, two-way divided traffic, speed limit above 50 mph, commercial location, and collision with a barrier as the first harmful event

Within C2 of the fixed object collision motorcycle crash data, the highest association, represented by the highest bar on the right side of the chart (see Figure 6), is with median presence. This association involves roads with a positive barrier median, shoulders on both sides, two-way divided traffic, speed limits higher than 50 mph, commercial areas, collision with a barrier as the first harmful event, and one-way traffic. Such roads usually belong to major highways or expressways, where high-speed traffic is common due to their design and purpose. These roads are often found in urban areas with a significant volume of commercial activities and multiple lanes to accommodate heavy traffic flow. This finding was consistent with previous studies suggesting that a motorcyclist was more likely to be killed or severely injured in a traffic crash that occurred on a major road as compared with a local road (Eustace et al., 2011; Savolainen & Mannering, 2007).

4.2.3. Cluster 3 (C3)—Injury crashes occurred unknown median type, unknown shoulder type, unidentified land use, rolling/mountainous terrain, and unknown trafficway in dark-unlighted conditions

In the fixed object collision motorcycle injury crash data for C3, the most prominent association, represented by the tallest bar on the right side of Figure 6, is linked to the unknown presence of a median. This correlation pertains to roads with unspecified median type, unknown shoulder type, unidentified land use, in rolling/mountainous terrain, unknown trafficway, and occurring in dark-unlighted conditions. This analysis brought to light a significant portion of the dataset containing missing information, particularly concerning the unrecorded details about both shoulders and medians for crashes in this cluster. These types of roads are often found in rural or less densely populated areas, where terrain features, such as mountains or hills are more prevalent. The findings from Shaheed et al. (2011) study, as mentioned in C3 of fatal crashes, further support this lighting condition observation.

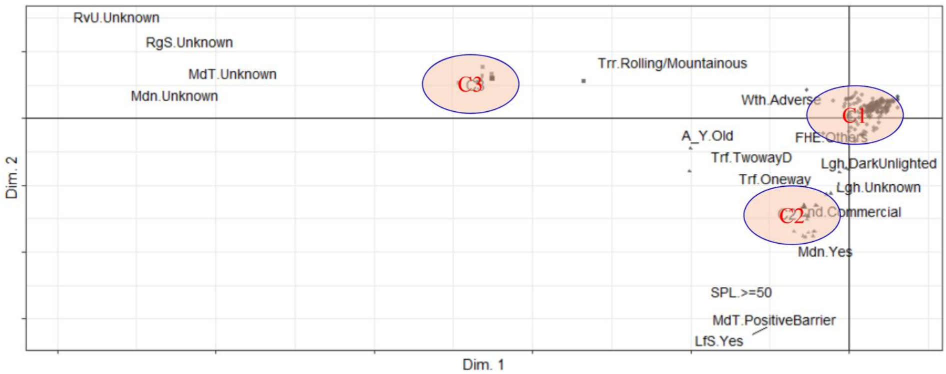

Figure 7. Correspondence analysis plot in PDO crashes.

4.3. PDO crashes

As shown in Figure 7, C1 constituted about 85% of PDO crashes. Similar to both fatal and injury crashes, there was a strong association between two-way undivided roads without right/left shoulders, a speed limit of <30 mph, and collision with fixed object as the first harmful event. In addition, crashes involving a positive barrier on dark and unlighted two-way undivided roads were dominant in C2. Finally crashes involving older drivers under adverse weather conditions on rolling and mountainous terrains were also found in C3, constituting 4.3% of PDO crashes.

4.3.1. Cluster 1 (C1)—PDO crashes occurred on roads with no median, two-way undivided, no right or left shoulder, and speed limit <30 mph

In the fixed object collision motorcycle PDO crash data for C1, the most notable association, depicted by the tallest bar on the right side of Figure 8, is linked to roads without a median. This correlation involves two-way undivided roads with no right shoulder, situated in rural areas, lacking a left shoulder, and with a speed limit of <30 mph. The first harmful event in these crashes is identified as collision with other fixed objects. Such roads are most probably in local neighborhoods, rural areas, or some urban streets. It was also observed in Salum et al. (2019) that PDO crashes were significantly associated with streets and roads.

4.3.2. Cluster 2 (C2)—PDO crashes occurred on roads with both-side shoulders, positive barrier median, two-way divided traffic or one-way traffic, speed limit above 50 mph, commercial location, and under dark not lighted conditions

Within C2 of the fixed object collision motorcycle PDO crash data, the highest association, represented by the highest bar on the right side of the chart (see Figure 8), is with the presence of a right shoulder. This association

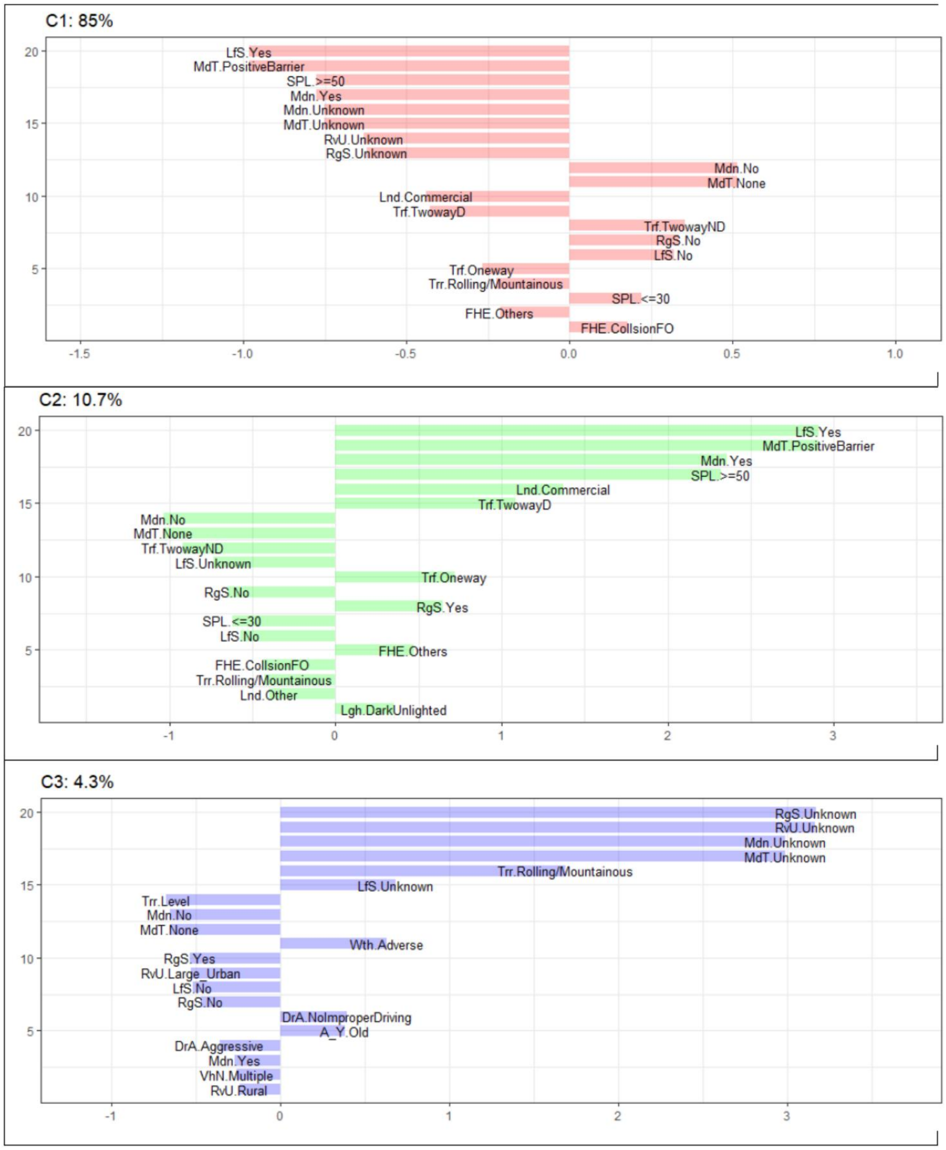

Figure 8. Clusters in PDO crashes.

involves roads with a positive barrier median, shoulders on both sides, two-way divided traffic or one-way traffic, speed limits higher than 50 mph, and in commercial areas. Such roads usually belong to major highways or expressways, where high-speed traffic is common due to their design and purpose. These roads are often found in urban areas with a significant volume of commercial activities and multiple lanes to accommodate heavy traffic flow. The findings from Zhang's study (37), as mentioned in C3 of fatal crashes, further support this observation of lighting conditions.

4.3.3. Cluster 3 (C3)—PDO crashes occurred unknown shoulder type, unidentified land use, unknown median type, rolling/mountainous terrain, unknown trafficway in adverse weather condition, with no proper diving action

In the fixed object collision motorcycle PDO crash data for C3, the most prominent association, represented by the tallest bar on the right side of Figure 8, is linked to the unknown presence of a right shoulder. This correlation pertains to roads with unidentified land use, unknown median type, rolling/mountainous terrain, unknown trafficway in dark-lighted conditions, under adverse weather conditions, with no proper diving action. This analysis brought to light a significant portion of the dataset containing missing information, particularly concerning unrecorded details about shoulders, land use, and medians for crashes in this cluster. These types of roads are often found in rural or less densely populated areas, where terrain features, such as mountains or hills are more prevalent.

The overall trend remains highly consistent across all three levels of crashes. The first cluster is characterized by roads without a median, which are two-way undivided, and lack both right and left shoulders, with a speed limit of <30 mph. The C1 collisions are associated with other fixed objects, and the C2 collisions involve rural roads with both-side shoulders, positive barrier medians, either two-way divided or one-way traffic, a speed limit above 50 mph, and are predominantly located in commercial areas where PDO crashes (but not injury and fatal crashes) are associated with dark hours. Besides, fatal crashes are associated with multiple occupants, while PDO and injury crashes are not. The C3 crashes comprise roads with unknown shoulder type, unidentified land use, and unknown median type, situated in rolling/mountainous terrain. In this cluster, PDO crashes are associated with unknown trafficway, adverse weather conditions, and a lack of proper diving action, whereas fatal and injury crashes are related to dark-unlighted conditions.

4.4. Analysis of clustered dataset

Despite the figures (Figures 4, 6, and 8) showing the 20 variables with the highest standardized residuals, there may be other variables that are also worth exploring. These variables may not have made it into the top 20 because they are not as strongly correlated with the dependent variable, but they could still be important predictors. Table 3 was prepared to examine the distribution of all variables relevant to each crash observation utilized in this study. The findings from Table 3 will be elaborated upon in the subsequent sections.

Table 3. Distribution of variable attributes by clusters in each injury type.

	Fatal			Injury			PDO		
Variable	C1 $N=61$	C2 $N=10$	C3 $N=5$	C1 $N=715$	C2 $N=167$	C3 $N=53$	C1 $N=159$	C2 $N=20$	C3 $N=8$
VehNum (number of involved vehicles)									
Multiple	6.6	20.0	0.0	8.4	13.2	5.7	12.6	20.0	0.0
Single	93.4	80.0	100.0	91.6	86.8	94.3	87.4	80.0	100.0
Age_Y (driver)									
Young	19.7	20.0	20.0	23.9	21.0	24.5	22.0	30.0	37.5
Middle	67.2	70.0	80.0	69.0	71.9	67.9	66.7	65.0	50.0
Old	11.5	10.0	0.0	5.9	7.2	7.6	2.5	5.0	12.5
Unknown	1.6	0.0	0.0	1.3	0.0	0.0	8.8	0.0	0.0
DriverAction (actions of drivers)									
Aggressive	49.2	70.0	80.0	29.8	26.3	30.2	26.4	20.0	0.0
FailedtoYeild (failed to yield)	0.0	0.0	0.0	0.8	1.8	1.9	3.1	0.0	0.0
Inattention	1.6	0.0	0.0	6.7	4.2	3.8	5.0	5.0	12.5
NoImproperDriving (no improper driving)	1.6	0.0	0.0	19.9	26.9	24.5	30.2	35.0	62.5
Others	47.5	30.0	20.0	42.8	40.7	39.6	35.2	40.0	25.0
FHE (first harmful event)									
CollisionB (collision with a barrier)	29.5	90.0	80.0	46.3	72.5	35.8	38.4	50.0	37.5
CollsionFO (collsion with other fixed objects)	65.6	10.0	20.0	47.1	19.8	56.6	49.7	20.0	37.5
Others	4.9	0.0	0.0	6.6	7.8	7.6	11.9	30.0	25.0
Lighting									
DarkLighted (dark lighted)	24.6	40.0	20.0	18.0	19.8	17.0	23.9	10.0	25.0
DarkUnlighted (dark unlighted)	16.4	30.0	40.0	7.0	9.0	15.1	6.3	15.0	0.0
DawnDusk (dawn or dusk)	14.8	0.0	0.0	5.3	2.4	9.4	5.7	10.0	12.5
Daylight	42.6	30.0	40.0	68.7	67.7	58.5	62.9	60.0	62.5
Unknown	1.6	0.0	0.0	1.0	1.2	0.0	1.3	5.0	0.0
Trafficway									
Oneway	1.6	10.0	20.0	6.6	15.6	11.3	7.6	30.0	12.5
TwowayD (two way divided)	6.6	90.0	40.0	17.8	77.8	17.0	17.6	70.0	37.5
TwowayND (two way undivided)	90.2	0.0	40.0	74.4	6.0	67.9	72.3	0.0	50.0
Unknown	1.6	0.0	0.0	1.3	0.6	3.8	2.5	0.0	0.0
Weather									
Adverse	3.3	0.0	0.0	3.2	4.8	1.9	8.8	10.0	37.5
Clear	96.7	100.0	100.0	96.8	95.2	98.1	91.2	90.0	62.5
SPL (speed limit)									
≤30 mph	34.4	0.0	0.0	42.8	22.8	26.4	42.1	5.0	37.5

≥50 mph	3.3	60.0	40.0	1.3	40.1	5.7	1.3	65.0	0.0
30–50 mph	36.1	20.0	20.0	23.8	16.2	28.3	21.4	10.0	25.0
Unknown	26.2	20.0	40.0	32.2	21.0	39.6	35.2	20.0	37.5
LeftShoulder (left shoulder)									
Yes	0.0	60.0	0.0	0.3	51.5	0.0	0.0	85.0	0.0
No	68.9	40.0	0.0	56.2	43.7	3.8	57.2	15.0	0.0
Unknown	31.1	0.0	100.0	43.5	4.8	96.2	42.8	0.0	100.0
RightShoulder (right shoulder)									
Yes	52.5	80.0	0.0	46.3	74.3	1.9	51.6	95.0	0.0
No	45.9	20.0	0.0	52.7	25.7	0.0	47.8	5.0	0.0
Unknown	1.6	0.0	100.0	1.0	0.0	98.1	0.6	0.0	100.0
Median									
Yes	1.6	90.0	0.0	0.3	95.8	1.9	5.0	90.0	0.0
No	98.4	10.0	0.0	99.6	3.0	0.0	95.0	0.0	0.0
Unknown	0.0	0.0	100.0	0.1	1.2	98.1	0.0	10.0	100.0
MedianType (median type)									
PositiveBarrier (positive barrier)	0.0	60.0	0.0	0.0	68.9	1.9	0.0	85.0	0.0
Unknown	0.0	0.0	100.0	0.1	1.2	98.1	0.0	10.0	100.0
None	98.4	0.0	0.0	99.2	1.2	0.0	95.0	0.0	0.0
Other	1.6	40.0	0.0	0.7	28.7	0.0	5.0	5.0	0.0
RvsU (rural or urban)									
Large_Urban (large urban)	72.1	90.0	20.0	80.1	90.4	20.8	79.2	75.0	12.5
SmallUrban (small urban)	16.4	10.0	20.0	10.1	8.4	1.9	8.8	15.0	0.0
Rural	11.5	0.0	0.0	9.7	1.2	0.0	11.9	10.0	0.0
Unknown	0.0	0.0	60.0	0.1	0.0	77.4	0.0	0.0	87.5
Terrain									
Level	86.9	100.0	20.0	87.6	95.8	13.2	88.1	100.0	0.0
Rolling/mountainous	11.5	0.0	80.0	11.3	4.2	79.2	11.3	0.0	100.0
Unknown	1.6	0.0	0.0	1.1	0.0	7.6	0.6	0.0	0.0
Landuse (land use)									
Commercial	1.6	30.0	0.0	3.1	29.9	0.0	5.0	45.0	0.0
Residential	1.6	0.0	0.0	5.3	1.8	0.0	4.4	0.0	0.0
Other	96.7	70.0	100.0	91.6	68.3	100.0	90.6	55.0	100.0

Note: Yellow color in the cells represents lower values. Light green bars indicate moderate values, while dark yellow bars signify higher values.

4.4.1. Driver characteristics

Considering driver's demographics, middle aged drivers were the largest group of drivers associated with all types of injury severity. This could potentially be attributed to their larger population among bike riders. Younger drivers constituted about 20%, 23%, and 30% of fatal, injury, and PDO crashes, respectively. Comparing the percentage of injuries associated with younger drivers, one can see that younger drivers are more likely to be injured than to be killed or not injured in fixed object crashes. This is the opposite for older drivers, as on average 10% of crashes involving older drivers are fatal as compared to an average of 7% for both injured and PDO crashes. This finding is in line with previous studies that acknowledged that older drivers are more likely to die in fixed object crashes due to their declining physical conditions as compared to younger motorcyclists (Amiri et al., 2020; Schneider & Savolainen, 2011). Other studies also tie the high rate of fatalities among older motorcyclists to their slow reaction time and reduced sensory and perceptual ability (Pai & Saleh, 2007; Savolainen & Mannering, 2007).

For drivers' actions before the crash, aggressive driving contributed to a significantly high percentage of fatal crashes (66%) as compared to injury and PDO. On the other hand, no fatal injury is associated with a driver's failure to yield the right of way. This could be due to the lower speed associated with failure to yield-related crashes as they usually occur at intersections. In addition, driver's inattention contributed to a lower percentage of crashes across all clusters while a higher number of injured and PDO crashes are related to no improver driving.

4.4.2. Crash characteristics

Collisions with barriers and fixed objects were found to be the two main first harmful events associated with fixed object crashes. As shown in Table 3, more crashes were fatal when motorcyclists collided with other fixed objects as compared to barriers. This could be attributed to road barriers being designed to absorb some level of force while redirecting the energy of motorcycles, which is not the same for fixed objects like embankments and trees (Jenson et al., 2021). Almost an equal number of crashes involving fixed objects and barriers resulted in injury and PDO crashes. Single-vehicle crashes also formed the majority of fixed object-related crashes for all three injury severity types.

Concerning lighting conditions, the majority of crashes occurred under daylight conditions across all clusters for different injury severities. Comparing dark-lighted and dark-not lighted conditions, a higher percentage of fatalities were associated with dark but lighted roads. Perhaps people tend to use motorbikes more when the road is lighted since motorcyclists rely greatly on visibility during driving. A significant percentage of crashes were also recorded under dawn and dusk lighting conditions. In terms of weather, crashes occurring under clear weather conditions clearly outnumber crashes under adverse weather for all clusters under different injury severities. This is expected as, unlike cars, motorcycles do not offer protection against weather conditions and motorcyclists are most likely to use motorcycles only during clear weather. However, a larger percentage of crashes under adverse conditions were PDO crashes. This finding could also be attributed to motorcyclists driving carefully and slowly due to the condition of the road pavements caused by adverse weather.

In terms of land use, commercial areas recorded more fatal, injury, and PDO crashes than residential areas. Jimenez et al. (2015) attributed a higher number of motorcyclist crashes in commercial areas to lower perceptions caused by the visual overload of the motorcyclist. Motorcyclists may not notice objects until the last minute or after the crash. In addition, there was a significantly large proportion of fatal, injury and PDO crashes in small urban and large urban areas as compared to rural areas. This is also expected as more people use motorcycles in urban areas to escape traffic on roads.

To address the safety concerns associated with fixed object-related motorcycle crashes, some potential countermeasures can be suggested. Firstly, enhancing road barrier designs to better accommodate motorcycles could reduce the severity of crashes when colliding with barriers. Implementing crash cushions or energy-absorbing barriers can help redirect the energy of motorcycles, minimizing impact forces during collisions. Secondly, increasing visibility on roads, especially during dusk and dawn, can be achieved by improving road lighting systems. Thirdly, education and awareness campaigns targeted at motorcyclists can also play a crucial role in promoting safe riding practices. Emphasizing the importance of wearing protective gear, following speed limits, and avoiding reckless driving behavior can contribute to a safer road environment for motorcyclists. Additionally, road maintenance and improving the quality of road pavements, particularly during adverse weather conditions, can help prevent skidding and loss of control, which are common in PDO crashes under such conditions. In urban areas, traffic management strategies, such as providing designated motorcycle lanes and implementing traffic calming measures, can help reduce the number of motorcycle crashes and improve overall road safety.

4.4.3. Traffic and road characteristics

Regarding road and traffic characteristics, a relatively higher number of fatal, injury, and PDO crashes were recorded on two-way undivided roads as compared to two-way divided roads. The disparity in the number of crashes in these two types of roads could be due to undivided roads being smaller than roads divided with medians, giving riders less room to operate. Similar results can be seen in the percentage of crashes occurring on roads with and without medians. A majority of fatal, injury, and PDO crashes were recorded on roads without medians or positive barriers. Medians generally reduce traffic conflicts, and so their absence might increase the number of crashes (Kim et al., 2007; Tamakloe et al., 2022). Furthermore, roads without a left shoulder had a high number of fatal, injury, and PDO crashes. Surprisingly the opposite was found for roads with right shoulders. The average percentage of fatal crashes recorded on roads with right shoulders was higher than on roads without right shoulders. Since shoulders are designed to add more room to roads for safe maneuvers, this anomaly needs to be further investigated. Level terrains were also observed to have a higher number of crashes than rolling/mountainous terrains for all crash types. With regards to speed, roads with speed limits between 30 and 50 mph recorded a significantly higher number of fatal crashes, while roads with speed limits $\leq$30 mph were mostly linked with injury and PDO crashes.

To improve road safety and reduce crash frequencies, some countermeasures can be recommended. For two-way undivided roads, enhancing road geometry and widening lanes can provide riders with more space to operate safely. Additionally, targeted road design modifications and traffic calming measures can be implemented on level terrains with higher crash rates.

5. Conclusions

This study investigated motorcycle crashes related to fixed objects using 1,198 crash observations collected over a 5-year period (2016–2020) in Massachusetts. After extensive data conflation, crash contributing factors related, but not limited, to driver's demographics and actions, weather and lighting conditions, road features, and traffic characteristics were used. Using the CCA, a novel clustering method, fresh insights were determined which have the potential to greatly inform and tailor road safety measures. This study first separated the data based on severity levels (i.e. fatal, injury, and PDO). The CCA method was used on each of the three datasets and 3 clusters were generated each from the three datasets. Each cluster encompasses crash observations with similar attributes.

The study identified distinct risk factors associated with different crash severity clusters. For fatal injury crashes, risk factors included low-speed two-way undivided roads without a median or shoulder, collisions with other fixed objects, and dark-unlighted conditions on rolling/mountainous terrains. Injury crashes were linked to roads without medians, two-way undivided traffic, speed limits below 30 mph, and collisions with barriers in rural settings. PDO crashes were associated with roads lacking medians, two-way undivided traffic, and speed limits below 30 mph, as well as dark-unlighted conditions and adverse weather on rolling/mountainous terrains. Older drivers were overrepresented in fatal crashes, while younger drivers were more prone to injury or PDO crashes. Reckless driving behavior also increased the likelihood of fatal crashes. Moreover, crashes lacking medians or positive barriers were more likely to result in fatal and injury outcomes.

Based on the results, several policy and safety engineering measures can be recommended to mitigate motorcycle crashes involving fixed objects. From a policy perspective, there is a clear need for targeted road design interventions in areas prone to fatal and injury crashes, such as low-speed, two-way undivided roads, and roads lacking medians or positive barriers. Implementing median barriers, roadside barriers suitable for motorcyclist safety, or improving shoulder designs on such roads could significantly reduce crash severity. Additionally, enforcement of speed limits and enhanced lighting on rural and mountainous terrains would address the high-risk conditions identified in fatal and injury clusters. Safety engineering measures should also include the installation of rumble strips and reflective signage in dark, unlighted areas to enhance driver awareness. For older drivers, targeted awareness campaigns focusing on high-risk behaviors and environments, such as reckless driving in low-visibility areas, could be effective. Furthermore, municipalities should prioritize road maintenance and install traffic-calming measures in areas identified as high-risk for motorcycle crashes. These countermeasures could provide a safer environment for motorcyclists and reduce the severity of fixed object-related crashes.

Understanding the distinct patterns of motorcycle crashes involving fixed objects provides critical insights for improving road safety and developing targeted countermeasures. However, the study has some limitations. First, the analysis focuses solely on crash data from Massachusetts, which may limit the generalizability of the findings to other regions or states with different road environments and traffic conditions. Additionally, missing or incomplete data (for example, involved vehicle type, rider specific details) could have introduced biases or inaccuracies in the results. Another limitation is that the clustering approach, while effective in revealing patterns, may not capture all possible risk interactions or nuances, particularly in cases with complex, overlapping factors. Importantly, the impact of COVID-19 was not explicitly considered in this study. Although the total number of motorcycle-fixed object crashes did not change significantly during the pandemic years, future research should explore whether changes in rider behavior, traffic patterns, or other external factors during the COVID period influenced crash outcomes. Studies like Das et al. (2022), Weng et al. (2021), and Xiao et al. (2024) insights on how data-driven approaches can enhance future analyses of crash patterns. Incorporating these advanced techniques could improve the depth of analysis in future studies. Additionally, expanding the dataset to include multiple states and conducting longitudinal analyses could offer a more comprehensive understanding of crash patterns and trends, enabling the development of more effective and data-driven safety measures.

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