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Pattern Identification from Older Bicyclist Fatal Crashes

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Abstract
Estimates from the U.S. Census Bureau indicate that the elderly (age 65 and older) people represented 12% of the total population in 2005. Bicycling is becoming popular among people of all groups. In 2016, 130 elderly bicyclists were killed (20% higher than 2014) on the U.S. roadways. The sharp rise of elderly bicyclist fatal crashes calls for a rigorous study to determine the key associated factors in elderly bicyclist crashes. Graphical methods, such as joint correspondence analysis (JCA), are useful in identifying the association patterns from a complex data set with multiple variables by producing a proximity map of the variable categories in a low dimensional plane. This study used 3 years (2014 to 2016) of data on elderly bicyclist fatal crashes from the Fatality Analysis Reporting System (FARS) in the U.S. to determine the key associations between the contributing factors by using JCA. Some of the key findings include bicyclist fatal crashes on roadways with high posted speed being very random; higher crash occurrences on roadways with bicycle lane/shoulder/parking lane under dark conditions with no lighting, on two-way undivided roadways with bicyclists on the travel lane, and at signalized intersections (pedestrian/bicycle signal presence is unknown) with "motorists fail to yield" related crashes. The findings from the current study can help in refining the policies and safe design practices that explicitly recognize this issue and will better serve a growing segment of the nation's population.

Bicycling is gaining popularity among people of all ages. It is considered a convenient mode of transport for recreational purposes. Because bicyclists are vulnerable road users, their increased number also increases the need for safe roadway design, especially for elderly bicyclists, considered as being 65 years old or above. There were 818 bicyclist deaths in 2015 which accounted for 2.3% of all traffic fatalities during the same year. Over a period of 10 years from 2006 to 2015, the average age of bicyclists killed in motor vehicle crashes increased from 41 to 45. In 2016, 130 elderly bicyclists were killed on U.S. roadways. This number is 20% higher than the fatalities of elderly bicyclists in 2014 (*1*). This sharp increase calls for in-depth analysis for identifying the key contributing factors in elderly bicyclist fatal crashes.

The profession has used a variety of terms and definitions to describe the demographic category that is the focus of this paper. In previous versions of their series of handbooks, for example, the Federal Highway Administration (FHWA) used the term "older driver"; they discussed several alternatives before deciding to use the term "aging" to describe the population group for the latest *Handbook for Designing Roadways for the Aging Population* (*2*). Other agencies and other reports and resources have used terms such as "elder" or "elderly." Each of the above has connotations that may be received differently, depending on the intended audience. Similarly, researchers and demographers have used a variety of thresholds to define the limits of the group of road users in question, typically choosing minimum ages in multiples of 5 years beginning at 65 years of age. To provide consistency with FHWA and describe a clear definition, the term "65+ bicyclists" is used in this paper and describes bicyclists who are over 64 years old.

Conventional statistical methods pay little attention to data visualization and dimensionality reduction. Correspondence analysis (CA) is a tool that can fill this gap, allowing the data visualization element in understanding patterns and sequences by representing the data graphically. CA can easily accommodate larger data sets in a natural and intuitive way. This dimension-reducing

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step is a crucial analytical aspect of CA and can be performed only with a certain loss of information. However, the objective is to restrict this loss to a minimum so that the maximum amount of information is retained. The Burt matrix version of multiple correspondence analysis (MCA) shows that the problem lies in trying to visualize the whole matrix (*3*, *4*). In most of the cases, the major interest is in the off-diagonal contingency tables which cross-tabulate distinct pairs of variables. Joint correspondence analysis (JCA) concentrates on these tables, ignoring those on the diagonal, resulting in improved measures of total inertia and much better data representation in the maps. One of the major tasks in highway safety research is the identification of key contributing factors for different types of crashes. JCA is useful in describing the significance of co-occurrence of groups of variables or variable categories from a high-dimension dataset. The objective of this study is to investigate associations between multiple variables, as opposed to the more traditional characterization of associations between a set of predictor variables and a single response variable of interest (e.g., number of crashes). The approach methodology seems appropriate to accomplish the research goals.

Objectives

This study used 3 years (2014 to 2016) of data on 65+ bicyclist fatal crashes in the U.S. from the Fatality Analysis Reporting System (FARS). The advantage of using this database is that it provides more detailed information about crash occurrence scenarios. The objective of this paper is to apply JCA on 3 years of fatal crash data on 65+ bicyclists to identify key patterns in the contributing factors. The authors anticipate that the findings can help authorities in determining the most suitable and effective countermeasures for safe mobility of 65+ bicyclists.

Earlier Work and Research Context

With the fast-growing popularity of bicycling as a mode of transport, research interest in bicycle safety has also been gaining popularity among researchers (*5*, *6*). The literature review conducted under the scope of this paper has revealed that safety sector areas involving bicyclists that have received most research attention have involved investigation of injury severity and crash counts under the influence of different cycling behaviors and roadway design elements. However, few studies have looked at the elderly bicyclist fatal crash occurrence, which is the primary focus of this paper.

Matsui et al. studied the nature of and features related to fatal injury cases in older bicyclists in Japan aged 75 years and above (*5*). Fatal injuries were categorized by body regions, mainly the common injury locations such as head, chest, hip, and others. Chi-square tests were performed to compare the frequency and severity of these injury occurrences with bicyclists in other age groups. Their study showed that bicyclists involved in fatal crashes were found to have suffered multiple injuries. Head was found to be the most common region for fatal injury among both males and females. This study noted that the outcome and severity of bicycle crashes depend on the dynamic nature of vehicle–bicycle interaction at the time of the collision.

Schepers et al. examined cyclist fatality trends in on-road crashes with and without other vehicles in the Netherlands from 1996 to 2014 (*6*). The study showed that the occurrences of single cyclist fatalities had increased during the study period of 19 years. Similarly, Scholten et al. showed that the incidents of fatal head injury cases reported at Dutch emergency departments involving no other vehicles constituted more than half of total cyclist fatal injury incidents (*7*).

Whereas some studies have investigated fatality rates and causation based on injury location, and other crash scenarios for bicyclists only, a few studies have focused on the crash investigation of bicyclists with pedestrians, as both can be categorized as vulnerable road users. Bernhoft and Carstensen compared the behavior and preferences of older pedestrians and bicyclists (defined as 70 or above in age) by survey questionnaires in several cities in Denmark and compared the responses to those of respondents ranging between 40 and 49 years of age (*8*). Chi-square tests and logistic regression were used to examine the significance of differences. The findings suggest that the injury rate of older bicyclists is approximately three times than that of younger cyclists and that this is caused by multiple contributing factors. These include physical fragility, perception lag, and inability to process information and initiate response as quickly as their younger counterparts. The findings of the study are applicable for both gender groups.

A detailed review of the paper by Bernhoft and Carstensen (*8*) for obtaining a better understanding of comparison between older and younger bicyclists has revealed that cycle paths are considered to be the most important factor by both the younger (age 40–49) and older groups of bicyclists. However, there is a statistically significant difference between the preferences of young and old bicyclists. Other factors showing the statistical differences include signalized crossings, the presence of smooth surface on cycle paths or roads, marked cycle lane in crossings, and absence of other skaters or bicyclists on the path. Older bicyclists consider the absence of cycle paths more dangerous than younger bicyclists do and take it into account while making route choices more often than young bicyclists do. Contrarily, young bicyclists consider it more dangerous to ride where there are parked cars and go straight through when there are right turning vehicles. Older bicyclists are significantly less likely to violate traffic movements (e.g., run red lights, ride on a traffic lane, and ride in the opposite direction on cycle paths) which are prohibited under Danish laws. In general, both older pedestrians and bicyclists display more careful and cautious behavior than younger bicyclists in specific traffic situations. The paper concluded that increased knowledge of pedestrian and cyclist preferences and behavior in traffic situations can help design a more accommodating transportation system and minimize areas of conflict. The authors also state that some of the differences in behavior and preferences can be ascribed to changing social and demographic effects rather than just age effect.

Bicyclists are a separate group of road users that are subjected to the same level of exposure to roadway collision scenarios as other vehicles for sharing the same right of way. However, looking into pedestrian-related crash investigation studies can also provide insights that will help identify the vulnerability of bicyclists to the same degree in an event of a crash occurrence. In an earlier study in Denmark, Rosenkilde observed that older pedestrians had difficulty in crossing the road whether or not crossing facilities were present (*9*). This led to the introduction of more accommodating and forgiving road crossing facilities such as pedestrian islands on the median, reduction of road widths, and so forth. Similarly, Zegeer et al. found that dense traffic reduces older pedestrians' ability to identify sufficient gaps in traffic while crossing (*10*). They also found in an experiment that less than 10% of older pedestrians had crossing speeds that are considered "normal" for pedestrian signal timing purposes (*11*, *12*).

Schreibman et al. examined 10 years of injury registration data (1997 to 2006) from Sweden to investigate the injury types, mechanisms, and consequences for bicyclists who are 65 years and older (*13*). Alcohol impairment was found to be only a minor contributing factor (less than 2%) in bicycle-related crashes. The authors recommended that preventative strategies specifically aimed at the elderly bicyclist user group should be developed to create more interest in this mode of transportation and reduce the health and medical cost effects of such a choice.

Cross and Fisher utilized data collected from interviews and on-site investigations in four urban and rural areas in the United States to identify crash contributing factors and associated countermeasures to address vehicle–bicycle crashes (*14*). Crash incidents were classified by problem types including the cause of crash, traffic context, and target group. These problem types accounted for operator (driver) characteristics, vehicle characteristics, characteristics of accident trip, environmental factors, characteristics of the crash location, and so forth. Researchers found that the 10 most frequent problem types out of the total of 30 problem types accounted for approximately two-thirds (67%) of fatal and 64% of non-fatal crashes. The study recommended countermeasures with the highest accident reduction potential for each of the problem types.

Pedestrian and bicyclist crash scenarios in the United States have also been studied by Sherony and Zhang, who analyzed National Highway Traffic Safety Administration (NHTSA) data from the years 2000 to 2013, and concluded that crash severity was higher in bicyclist and pedestrian accidents involving older users (age 70 and above) than in other age groups (*15*).

MacAlister and Zuby studied the most common fatal crash scenarios for vehicle–bicycle crashes in the U.S. using national crash databases (*16*). The greatest contribution to fatal crashes came from nighttime crashes and on streets with speed limits greater than 40 mph. The study found that in the U.S. context, the most common crash scenario involved crossing paths from bicyclist and traffic streams. The most common fatal scenario was a cyclist being struck by a motor vehicle along the same traffic stream. The study concluded that crash detection systems that work in both daytime and nighttime and on high-speed facilities provide the highest benefit for detection in these overrepresented crash scenarios.

Salon and McIntyre substantiated the growing concern of pedestrian and bicyclist safety in the United States, particularly in the urban context (*17*). Logistic regression models were developed using 10 years of crash data from San Francisco, California, to identify key contributing factors to crash severity in crashes involving nonnotarized road users. The hypothesis that environmental factors influencing driver speed and reaction time have an important role to play particularly when the driver is not at fault was tested by classifying the crash incidents by the person or party at fault. The results for pedestrians were found to be consistent with previous research but the effect was much weaker for bicyclists and the classification by party at fault was observed to be less significant.

The findings of the current literature review help identify contributing factors to bicycle crashes; however, understanding the overall mechanism leading to bicyclists' fatal or injury crash occurrence, especially for 65+ bicyclists, with a view to finding potential engineering countermeasures, requires a more extensive and innovative statistical approach. There are many traffic safety studies, especially from recent years, pertaining to the use of data mining and CA methods (*18–35*) to diagnose clusters of potential factors in complex databases.

Because of the nature of the data and associated research objectives, JCA, a modified variant of CA, is a good fit for the analysis. Considering other CA variants, JCA has the capacity for higher variable explanation and better data representation.

Data

FARS Crash Data

Limitations in information gathered about events preceding a pedestrian or bicyclist crash can hamper the development of effective countermeasures to prevent such crashes. To mitigate this gap, pedestrian and bicycle crash typing was developed to describe the pre-crash actions of the involved parties to better define the sequence of events and precipitating actions leading to crashes between motor vehicles and pedestrians or bicyclists. The data used in this study come from FARS, which is maintained by the NHTSA. In 2010, the NHTSA adopted parts of a standalone crash typing application called the Pedestrian and Bicycle Crash Analysis Tool (PBCAT) into FARS (*36*). Starting from 2014, FARS data now contains a large set of key information about bicycle crashes. These variables are:

- PB30B—Crash type—Bicycle
- PB31B—Crash location—Bicycle
- PB32B—Bicyclist position
- PB33B—Bicyclist direction
- PB38B—Crash group—Bicyclist

To accomplish the outlined research goal, this study used 3 years (2014 to 2016) of FARS data. Figure 1 shows the flowchart of the methodology applied in this study. Both bicyclist and other crash data were first extracted from FARS "PBTYPE" data. To identify the 65+ bicyclists, an age threshold (age 65 and above) was applied. Around 15% of all fatal bicyclist crashes involved elderly bicyclists. Later, both crash and vehicle crash data were merged with the 65+ bicyclist data by matching with the crash identification number. The final database contains 340 unique items of crash occurrence information and 350 of 65+ bicyclist information.

Data Preparation

The data preparation process is illustrated in the flowchart of Figure 1. The primary dataset contains 350 65+ bicyclist fatal crashes with 30 variables. Some of the variables are omitted because of redundancy. A crash group is selected in the final list for easy interpretation. The final data set consists of nine variables (bicyclist age, bicyclist gender, bicycle position during crash, traffic way type, traffic control, lighting condition, posted speed limit, number of lanes, and crash group), with 47 categories.

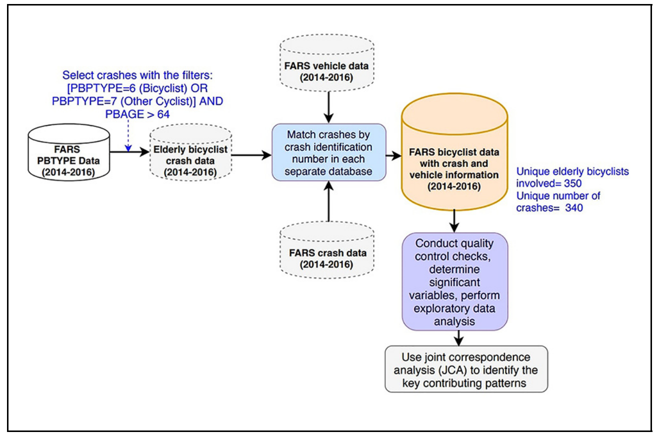

Figure 1. Flowchart of the methodology.

Descriptive Statistics

Descriptive statistics can provide insights into patterns in the data. Studies show that bicyclists of different age groups among the 65+ population show different patterns and inclinations (*6–12*). For this study, 65+ bicyclists were divided into four major age groups: 65 to 69 years, 70 to 74 years, 75 to 79 years, and over 79 years. Table 1 shows the percentage distributions of different attributes based on the ages of the 65+ bicyclists. Overall, the statistics show that the majority of the bicyclists were on the travel lanes. There is a higher proportion of bicyclists in the age groups 75 and above for bicyclists positioned on the travel lane. About 50% or more of bicycle fatalities occurred on two-way undivided roadways. Table 2 shows that 80% of these two-way undivided roadways had two lanes. There is a higher proportion of bicyclists aged 79 years and above in the fatal crashes associated with stop sign controlled intersections. Signalized intersections (not known if pedestrian/bicycle signal is present) show disproportionately high values in bicyclist (age 70 and above) fatal crashes.

Roadways with no controls (VTRAFCON) show relatively high proportions for 65- to 69-year-old bicyclists. Around 63% of these points are on the two-way undivided roadways. Additionally, around 74% of roadways with no controls are not intersection related. There is a relatively high proportion of bicyclists aged over 79 years on roadways with the posted speed limit of 25 mph or less. The majority of these low-speed roadways are two-way undivided.

Bicyclist fatal crashes are overrepresented on two-lane roadways. Signalized intersections with a pedestrian signal exhibit the lowest bicyclist fatal crash frequencies when compared with other traffic controls. Two-way undivided roadways with no controls and two-lane two-way undivided roadways experience over representative bicyclist fatal crashes. Bicyclist crashes at stop-controlled

Table 1. Percentage Distribution of Different Attributes by Age Groups

FARS Code	Variable	Attribute	Age: 65–69	Age: 70–74	Age: 75–79	Age: > 79
na	na	Number of bicyclists	146	96	54	54
BIKEPOS	Loc	Travel lane	69.86	66.67	77.78	75.93
BIKEPOS	Loc	Bicycle lane/ shoulder/parking lane	17.81	18.75	7.41	1.85
BIKEPOS	Loc	Sidewalk/crosswalk/driveway access	11.64	13.54	11.11	20.37
BIKEPOS	Loc	Unknown	0.68	1.04	3.7	1.85
VTRAFWAY	Road	Two-way undivided	54.79	61.46	61.11	53.7
VTRAFWAY	Road	Two-way continuous left turn	11.64	3.12	7.41	9.26
VTRAFWAY	Road	Two-way divided barrier	8.9	4.17	7.41	16.67
VTRAFWAY	Road	Two-way divided median	19.18	27.08	18.52	16.67
VTRAFWAY	Road	Others	5.48	4.17	5.56	3.7
VNUM_LAN	Lane	Two lanes	59.59	62.5	57.41	66.67
VNUM_LAN	Lane	Multilanes	35.62	33.33	38.89	29.63
VNUM_LAN	Lane	Others	4.79	4.17	3.7	3.7
VTRAFCON	TC	No controls	76.71	65.62	70.37	66.67
VTRAFCON	TC	Signal not known if pedestrian/bicycle signal	9.59	13.54	16.67	11.11
VTRAFCON	TC	Signal with pedestrian/bicycle signal	4.79	9.38	1.85	3.7
VTRAFCON	TC	Stop sign	6.85	5.21	5.56	12.96
VTRAFCON	TC	Others	2.05	6.25	5.56	5.56
LGT_COND	Light	Daylight	65.75	80.21	85.19	75.93
LGT_COND	Light	Dark—Lighted	14.38	7.29	11.11	9.26
LGT_COND	Light	Dark—Not lighted	13.7	7.29	1.85	5.56
LGT_COND	Light	Dawn/dusk	4.11	4.17	0	9.26
LGT_COND	Light	Others	2.05	1.04	1.85	0
PBSEX	Gen	Female	15.75	11.46	3.7	9.26
PBSEX	Gen	Male	84.25	88.54	96.3	90.74
VSPD_LIM	PSL	25 mph or less	8.9	9.38	3.7	18.52
VSPD_LIM	PSL	30–35 mph	21.23	32.29	40.74	38.89
VSPD_LIM	PSL	40–45 mph	33.56	23.96	31.48	37.04
VSPD_LIM	PSL	50–55 mph	25.34	23.96	14.81	1.85
VSPD_LIM	PSL	60 mph or above	10.96	10.42	9.26	3.7

Note: Intensity of the red color in the cells indicate higher percentage; na = not applicable; BIKEPOS = bicyclist position; VTRAFWAY = trafficway description; VNUM_LAN = total lanes in roadway; VTRAFCON = traffic control device; LGT_COND = lighting condition; PBSEX = gender; VSPD_LIM = posted speed limit.

intersections are overrepresented for age group 79 and above. Female bicyclists are overrepresented in the 65 to 69 age group. On the other hand, male bicyclists are overrepresented in 75 to 79 age group. For the age group 79 and above, only 5% of fatal crashes happened on roadways with higher posted speed limits (50 mph and above). One possible explanation is that very elderly bicyclists may usually avoid roadways with higher posted speed limits. However, this inference cannot be validated in this study because of the unavailability of age-based bicyclist exposure data.

Slope Graph Analysis

The variable "crash group" (PB38B) has 21 categories. Each crash group has different crash types (PB30B). For example, the crash group "motorist overtaking bicyclist" has four different categories: 1) motorist overtaking—undetected bicyclists, 2) motorist overtaking—misjudged space, 3) motorist overtaking—bicyclist swerved, and 4) motorist overtaking—other/unknown. The database contains 78 different crash types. The research team used the "crash group" variable for slope graph development and JCA because of its limited number of categories. The top 14 crash groups were selected for the slope graph development. This data visualization technique shows the ranking of a certain variable as an ordinal. For example, "motorist overtaking bicyclist" ranks first for three age groups (65 to 69, 70 to 74, 75 to 79 years), and drops to fourth for the age group 75 years and older. The slope graph (shown in Figure 2) clearly shows that the rankings of the top key factors are not the same for all age groups. For example, "bicyclist left turn/merge" holds the top rank among the bicyclists of age group 79 and above. This factor ranks

Table 2. Distribution of Trafficway Description by Number of Bicyclists (65 Years and above) Involved in Different Conditions

Attribute name	Two-way undivided	Two-way continuous left turn	Two-way divided median	Two-way divided barrier	Others
VNUM_LAN					
Two lanes	161	1	31	16	5
Multilanes	39	28	41	13	na
Others	1	na	1	1	12
BIKELOC					
At intersection	70	4	26	18	6
Intersection-related	18	5	10	1	1
Not at intersection	113	20	37	11	7
Other/unknown	na	na	na	na	3
VTRAFCON					
No controls	155	28	41	18	7
Signal not known if pedestrian/bicycle signal	15	na	17	9	1
Signal with pedestrian/bicycle signal	8	na	9	1	1
Stop sign	21	na	1	2	1
Others	2	1	5	na	7
VSPD_LIM					
25 mph or less	29	0	2	1	1
30–35 mph	71	6	18	5	5
40–45 mph	38	18	33	16	4
50–55 mph	50	4	10	5	0
60 mph or above	13	1	10	4	6

Note: na = not applicable; VNUM_LAN = total lanes in roadway, BIKELOC = bicyclist location, VTRAFCON = traffic control device, VSPD_LIM = posted speed.

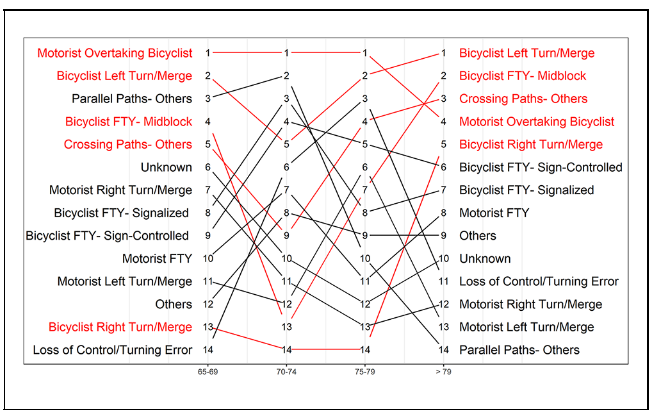

Figure 2. Slope graph of "crash group" by different 65+ bicyclist age groups.
Note: FTY = failed to yield.

second for the age group of 75 to 79 years. For the age group of 69 to 74 years, this factor ranks lower (fifth) and it jumps back to the second position among 65- to 69-year-old bicyclists. Another example is "bicyclists failed to yield–midblock." For this factor, the rank is second for the age group of 79 years and above whereas it goes down to seventh position and thirteenth position for age groups 75 to 79 and 70 to 74, respectively. It again goes up to the fourth position among 65- to 69-year-old bicyclists. "Motorists overtaking bicyclists" is ranked in the first position for three age groups (65 to 69 years, 70 to 74 years, and 75 to 79 years). Two factors show the highest slope between two age groups. These two are:

- "Bicyclist failed to yield–midblock," which jumps from fourth to thirteenth position between age groups 65 to 69 and 70 to 74.
- "Bicyclist right turn/merge," which moves from thirteenth or fourteenth to fifth when comparing the younger age groups (65 to 69, 70 to 74, or 75 to 79) with the oldest age group (79 years and above).

Joint Correspondence Analysis Overview

CA is a multivariate statistical approach for categorical data exploratory analysis. MCA and JCA are applications of CA to n-way frequency tables. JCA utilizes second-order moments, which are two-way marginal frequencies for categorical data. The one-way marginal frequencies are populated on the diagonal entries and the two-way margins occupy the non-diagonal spaces on the Burt matrix. Vermunt and Anderson proposed a maximum likelihood estimation for JCA by defining the model for a full n-way distribution (*37*). The advantage of this formulation over a standard weighted least squares approach is that goodness of fit tests can be performed with standard chi-square tests, thereby enabling comparison between alternative models. The traditional bivariate marginal distribution JCA model with marginal distributions $\Phi_{y_n y_m}^{Y_n Y_m}$ is of the following form:

$$\Phi_{y_n y_m}^{Y_n Y_m} = \Phi_{y_n}^{Y_n} \Phi_{y_m}^{Y_m} \left\{ 1 + \sum_{s=1}^{S} \alpha_s \mu_{sy_n}^{Y_n} \mu_{sy_m}^{Y_m} \right\} \tag{1}$$

where

$\Phi_{y_n}^{Y_n}$ represents the univariate marginal distribution entry for variable Y_n, and

$\mu_{sy_n}^{Y_n}$ represents the scale value of category y_n for variable Y_n and dimension s while α_s is the average correlation between the considered variables in dimension s.

Vermunt and Anderson (*27*) suggested the following extension for n-way tables:

$$\Phi_{y_1 y_2 \ldots\ldots y_n}^{Y_1 Y_2 \ldots\ldots Y_n} = \prod_{n=1}^{N} \Phi_{y_n}^{Y_n} \left\{ 1 + \sum_{s=1}^{S} \sum_{n=1}^{N} \sum_{m=n+1}^{N} \beta_s \omega_{sy_n}^{Y_n} \omega_{sy_m}^{Y_m} \right\} \quad (2)$$

which is known as the multivariate correlation model, the parameters of which can be estimated by maximum likelihood under a Poisson sampling scheme assumption.

Results and Findings

In JCA, the approach is to analyze the rows and columns of a dataset while treating them as high-dimension geometry elements. The aim is to show the co-occurrence of the categories in a lower dimensional space in which proximity in space potentially indicates meaningful associations among the categories. Graphical representations in JCA help to interpret data in a convenient way as they effectively summarize large, complex datasets by simplifying the structure of the associations between variable categories with a relatively simple view of the data. A larger distance between two attributes indicates an insignificant association. If the distance for a category is far away from the centroid, it indicates that such category is different from the average profile (*3*, *4*).

This study used the open-source R software package "ca" to perform JCA (*38*). Two well-known data visualization packages "ggplot2" and "ggrepel" were used to develop easily interpretable JCA plots (*39*, *40*). In this analysis, diagonal inertia discounted from eigenvalues is 0.023. The percentage explained by JCA in two major dimensions is 57.9%. The inertia explained in JCA is not axis based. This is a key difference in the application of the JCA. However, the inertia explained by the first plane is higher than the MCA. The number of iterations performed in this analysis is 26.

It is important to note that the contribution of variables depends on its number of categories, whereas the contribution of a category depends on the number of incidents coded under its categories. Figure 3 shows the JCA plot developed from the final data set. As placing 47 attributes in two dimensions is dense, three separate quadrant plots (Quadrants 2, 3 and 4) were developed in Figure 4 so that it is easier to see the results. To make the attributes readable in the plots, the limits of the axes

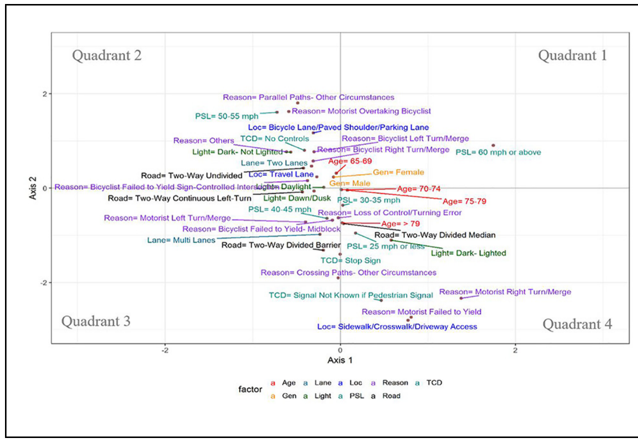

Figure 3. Relative closeness of the attributes shown in JCA plot.

are different in these plots. The general findings from the JCA plot are:

- It is found that posted speed limit of 60 mph and above is placed in the first quadrant. No other attribute is placed in that quadrant. Although 33 bicyclist fatal crashes were recorded on roadways with 60 mph or above posted speed limits, this attribute is not closely associated with any other attribute. This implies that the bicyclist fatal crashes on these roadways are random and are not associated with any pattern.
- Male and female bicyclists are seen in different quadrants. This implies that gender groups differ in association patterns. The proportion of male and female bicyclists involved in fatal crashes is higher for the age group 70 and above. The locations of the age group and gender types in the JCA plot supports this association.
- The quadrant with age group 65 to 69 years shows some patterns: posted speed limit = 50 to 55 mph, bicycle turning, either daylight or dark—not lighted, two-way undivided roads, bicyclists located either in the travel lane or in the bicycle lane.
- The quadrant with age group 70 years (and above) shows some patterns: low-speed roadways, motorist error, and divided roadways.
- The third quadrant shows two patterns: both motorist and bicyclist error, and moderate posted speed limit.

Figure 4 shows the placements of the attributes in each quadrant. The attributes with closer Euclidean distance are grouped in several clouds. The attributes generate six different clouds. Some general observations from these clouds are discussed below.

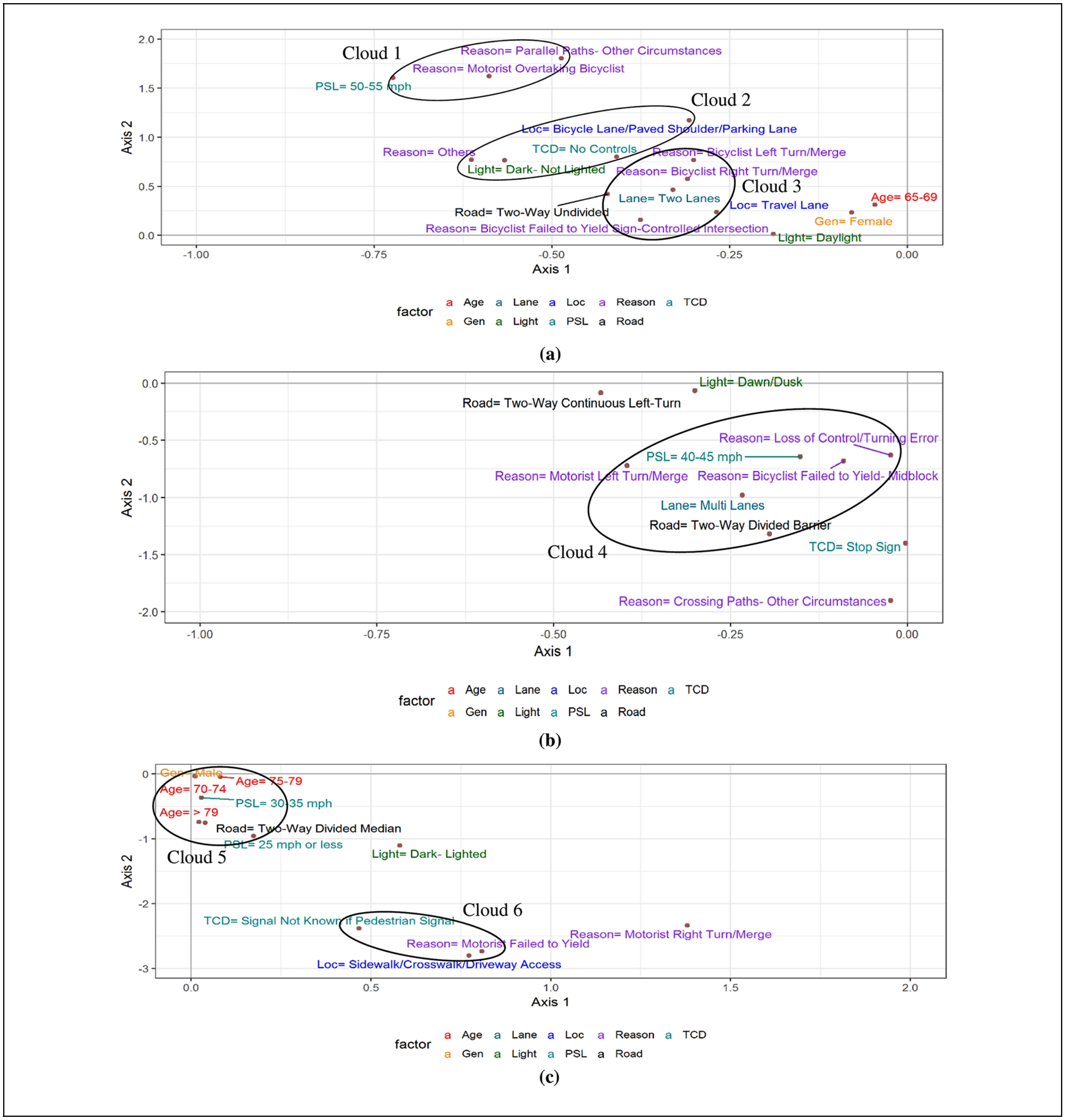

Figure 4. JCA plots by quadrants: (*a*) quadrant 2; (*b*) quadrant 3; (*c*) quadrant 4.

Cloud 1 (Posted Speed Limit = 50 to 55 mph, Motorist Overtaking Bicyclists, and Parallel Paths)

This cloud is visible in the second quadrant (see Figure 4*a*). It shows a close association between 50 and 55 mph posted speed limit roadways and "motorist overtaking bicyclists" or "parallel paths" related 65+ bicyclists crashes. A separated bike lane can be considered as a potential countermeasure for these locations. However, this countermeasure would be beneficial for all bicyclists (not limited to elderly bicyclists only).

Cloud 2 (No Traffic Control, Dark—Not Lighted, and Bicycle Lane/Paved Shoulders/Parking Lane)

This cloud indicates that crashes on a bicycle lane/paved shoulder/parking lane are associated with no traffic control and dark—not lighted conditions. Other studies also showed that driving and biking at night with no street lights is associated with more crashes (*41*, *42*). This cloud also offers the same inference. Enhanced nighttime street lighting would be beneficial at segments with high nighttime bicycle crashes. Additionally, sufficient conspicuity (e.g., wearing reflective gear at night) on the part of bicyclists would contribute to reducing these crashes.

Cloud 3 (Two-Way Undivided Roadways, Cyclist on Travel Lane, and Turning of the Bicyclists)

This cloud indicates an association between two-lane roads, two-way undivided roadways, cyclists on travel lane, and turning of bicyclists. Figure 2 shows that left turning is one of the top-ranking reasons for fatal bicyclist crashes. An exposure measure for bicyclists on two-lane roadways can help in identifying segments with higher volumes. Speed calming or sign messages can help motorists to be more aware of the presence of bicyclists on the roadway.

Quadrant 2, Outside of a Cloud

The second quadrant also shows three attributes with a close association which are not visible in any cloud. The variables include: female, 65 to 69 years of age bicyclists, and daylight. However, this pattern does not indicate any significant crash potentials. Table 1 shows that female bicyclists are overrepresented in the 65 to 69 age group. This finding is in line with the findings of Schoeman et al. (*13*), which showed that 65- to 74-year-old female bicyclists had a significantly higher incidence rate for crashes than female bicyclists aged 75 to 84 and 85 or more years. Failing to get these factors in the relevant cluster can be considered as a limitation of the JCA technique.

Cloud 4 (Multilane Divided, Moderate Speed, Motorist Left Turn, Bicyclists Failed to Yield, and Loss of Control)

This cloud shows the patterns of human-related errors on moderate speed multilane divided roadways (Figure 4*b*). The common crash group in this cloud includes left turn issues of the motorist, bicyclists failed to yield, and loss of control. Potential countermeasures include Barnes Dance, hybrid beacon, and bicycle intersection markings.

Quadrant 3, Outside of a Cloud

The third quadrant shows the association between dawn/dusk and the two-way continuous turn lane. Another two close attributes are the stop sign and crossing path. These two sets of associations show the high likelihood of these occurrences. This can be considered as a limitation of the JCA technique.

Cloud 5 (Bicyclists Age 70 and above, Male, Low Posted Speed Limit, and Two-Way Divided Median)

Table 1 shows that male bicyclists are overrepresented in the 70 and above age groups compared with the 65 to 69 age group. It also reveals that bicyclists of age 70 and above are overrepresented on roadways with a lower posted speed limit. This observation agrees with the findings of Bernhoft and Carstensen (*8*), which revealed some differences between the behavior of younger and 65+ bicyclists that include relative order of importance for presence of cycle paths, signalized crossings, smooth surface on cycle paths or roads, marked cycle lane in crossings, and absence of other skaters or bicyclists on path.

Cloud 6 (Motorist Failed to Yield, Driveway or Sidewalk, and Signalized Intersection Unknown if Pedestrian/Bicycle Signal)

This cloud indicates the association between signalized intersection (unknown if pedestrian signal), crash group, and the location of the bicyclists (Figure 4*c*). Several other studies showed that 65+ bicyclists have challenges with road crossing (*8*, *9*, *11*, *12*, *43*). Rosenkilde observed that the older pedestrians had difficulty in crossing the road whether or not there were crossing facilities (*9*). Schepers et al. and Scholten et al. showed that the occurrences of cyclist fatalities in cases involving no vehicles had increased and constituted a significant portion of total cyclist fatal injury incidents (*6*, *7*). Quadrant 4 shows a relationship between 70 years and above bicyclists and intersection-related crashes. Countermeasures such as the installation of a pedestrian (or bicyclist, perhaps) signal, modernized bicycle facility design with easier ride on-and-off features, and encouraging helmet wearing could be effective in reducing intersection-related bicycle fatal crashes. Potential countermeasures include Barnes Dance, hybrid beacon, high-visibility crosswalks, and bicycle intersection markings.

Conclusions

According to the U.S. Bureau of Labor Statistics, the percentage of 65+ people in the workforce who are 65 and above has increased from 10.8% in 1985 to 19.2% in 2017. In 2016, 130 65+ bicyclists were killed (20% higher than 2014) on U.S. roadways. As bicycling becomes more popular among all age groups, there is a need for an in-depth study to identify key patterns of 65+ bicyclist crashes.

This study attempted to identify the patterns of fatal crashes among 65+ bicyclists using statistical analysis to better understand the underlying association that leads to a fatal crash. JCA is performed on 3 years of fatal crash data for 65+ bicyclists obtained from FARS. This statistical approach helps discern associations between different variable categories or events to recognize an association mechanism behind a fatal crash occurrence. The key findings are the following:

- The proportion of male and female bicyclists involved in fatal crashes is higher for the age group 70 and above.
- 65+ bicyclist fatalities on roadways with the posted speed limit of 60 mph and above are random and are not associated with any other attribute included in this study.
- "Motorists overtaking the bicyclists" related crashes were mostly associated with roadways with 50 to 55 mph posted speed limit. Lowering the posted speed limit or providing a separated bike lane are potential countermeasures to reduce these crashes.
- Roadway with bicycle lane/shoulder/parking lane has a high likelihood of 65+ bicyclist fatal crashes at dark with no lighting. Providing lighting at high crash segments will reduce these crashes. Bicyclists with sufficient conspicuity at night (e.g., wearing reflective gear at night) would be considered as a potential treatment.
- Two-way undivided roadways with bicyclists on the travel lane are associated with turn-related bicyclists fatal crashes. Speed calming or sign messages would be beneficial in reducing these crashes.
- For multilane divided roadways, motorist left turning is associated with failure to yield related bicyclist fatalities. The signalized intersection (where the presence of a pedestrian/bicycle signal is unknown) is associated with "motorists fail to yield" related crashes. Barnes Dance, hybrid beacon, high-visibility crosswalks, and bicycle intersection markings are potential countermeasures.

The associations and patterns found in this study require additional attention for the safe mobility of age 65+ bicyclists. In many instances, it may be difficult for bicyclists alone to avoid crash occurrences. The Public Policy Institute (PPI) of the American Association of Retired Persons (AARP) conducted a research project and released the findings in a comprehensive public report, titled *Planning Complete Streets for an Aging America* (*44*). According to the report, a new approach for street design should be introduced in which, instead of favoring some types of vehicles over others, designers should focus on making the street safer for all road users by i) reducing travel speed (which can address Cloud 1 associated crashes), ii) making the road design easier to navigate (which can address crashes associated with Cloud 3 and Cloud 5), and iii) making the design more noticeable and understandable (which can address crashes associated with Cloud 4 and Cloud 6). The groups of factors contributing to bicycle crashes can be reduced by two major treatments—behavioral change of the 65+ bicyclists, and innovative design practices (e.g., Context Sensitive Solutions and Complete Streets) by designers and engineers. The current study helps identify contributing patterns for 65+ bicyclist crashes. Safe cycling practices, proper lane control and equipment, and sensitivity to roadway conditions and context can help mitigate risks.

Author Contributions

The authors confirm the contribution to the paper as follows: study conception and design: SD; data collection: SD; analysis and interpretation of results: SD, KJ, KF, THS; draft manuscript preparation: SD, KJ, KF, THS, MB. All authors reviewed the results and approved the final version of the manuscript.

References

1. National Highway Traffic Safety Administration. *2016 Data: Bicyclists and Other Cyclists: Traffic Safety Facts*. https://crashstats.nhtsa.dot.gov/Api/Public/ViewPublication/812507. Accessed July 27, 2018.
2. Brewer, M., D. Murillo, and A. Pate. *Handbook for Designing Roadways for the Aging Population*. Report No. FHWA-SA-14-015. Federal Highway Administration, Washington, D.C., 2014.
3. Le Roux, B., and H. Rouanet. *Multiple Correspondence Analysis*. Sage Publications, Thousand Oaks, CA, 2010.
4. Greenacre, M., and J. Blasius. *Multiple Correspondence Analysis and Related Methods*. Chapman & Hall/CRC, Boca Raton, FL, 2006.
5. Matsui, Y., S. Oikawa, and M. Hitosugi. Features of Fatal Injuries in Older Cyclists in Vehicle–Bicycle Accidents in Japan. *Traffic Injury Prevention*, Vol. 19, No. 1, 2018, pp. 60–65.
6. Schepers, P., H. Stipdonk, R. Methorst, and J. Olivier. Bicycle Fatalities: Trends in Crashes with and without Motor Vehicles in the Netherlands. *Transportation Research Part F: Traffic Psychology and Behaviour*, Vol. 46, 2017, pp. 491–499.
7. Scholten, A. C., S. Polinder, M. J. M. Panneman, E. F. van Beeck, and J. A. Haagsma. Incidence and Costs of Bicycle-Related Traumatic Brain Injuries in the

Netherlands. *Accident Analysis & Prevention*, Vol. 81, 2015, pp. 51–60.
8. Bernhoft, I. M., and G. Carstensen. Preferences and Behaviour of Pedestrians and Cyclists by Age and Gender. *Transportation Research Part F: Traffic Psychology and Behaviour*, Vol. 11, No. 2, 2008, pp. 83–95.
9. Rosenkilde, C. *Ældres Sikkerhed på Frederikssundsvej.* Dansk Vejtidsskrift, Vol. 5, 2001.
10. Zegeer, C. V., J. C. Stutts, H. Huang, M. Zhou, and E. Rodgman. Current Trends in Crashes to Older Pedestrians and Related Safety Treatments in the United States. In *Proc., Strategic Highway Research Program (SHRP) and Traffic Safety on Two Continents*, Hague, the Netherlands. Swedish National Road and Transport Research Institute (VTI), Linköping, Sweden, 1994, pp. 55–71.
11. Zegeer, C. V., J. C. Stutts, H. Huang, M. Zhou, and E. Rodgman. Analysis of Elderly Pedestrian Accidents and Recommended Countermeasures. *Transportation Research Record: Journal of the Transportation Research Board*, 1996. 1405: 56–63.
12. Zegeer, C. V., J. C. Stutts, H. Huang, M. Zhou, and E. Rodgman. Analysis of Elderly Pedestrian Accidents and Recommended Countermeasures. *Journal of Safety Research*, Vol. 2, No. 27, 1996, p. 128.
13. Scheiman, S., H. S. Moghaddas, U. Björnstig, P. O. Bylund, and B. I. Saveman. Bicycle Injury Events among Older Adults in Northern Sweden: A 10-Year Population Based Study. *Accident Analysis & Prevention*, Vol. 42, No. 2, 2010, pp. 758–763.
14. Cross, K. D., and G. Fisher. *A Study of Bicycle–Motor Vehicle Accidents: Identification of Problem Types and Countermeasure Approaches, Volume I*. DOT-HS-803-315, Na- , DOT-HS-803-315. National Highway Traffic Safety Administration, Washington, D.C., 1977.
15. Sherony, R., and C. Zhang. Pedestrian and Bicyclist Crash Scenarios in the US. *Proc., Intelligent Transportation Systems (ITSC), 2015 IEEE 18th International Conference*, IEEE, Canary Islands, Spain, 2015, pp. 1533–1538.
16. MacAlister, A., and D. S. Zuby. Cyclist Crash Scenarios and Factors Relevant to the Design of Cyclist Detection Systems. *Insurance Institute for Highway Safety*, Arlington, VA, 2015.
17. Salon, D., and A. McIntyre. Determinants of Pedestrian and Bicyclist Crash Severity by Party at Fault in San Francisco, CA. *Accident Analysis and Prevention*, Vol. 110, 2018, pp. 149–160.
18. Das, S., A. Dutta, and X. Sun. Patterns of Rainy Weather Crashes: Applying Rules Mining. *Journal of Transportation Safety & Security*, 2019. Advance online publication. https://doi.org/10.1080/19439962.2019.1572681.
19. Das, S., A. Bibeka, X. Sun, T. Zhou, and M. Jalayer. Elderly Pedestrian Fatal Crash-Related Contributing Factors: Applying Empirical Bayes Geometric Mean Method. *Transportation Research Record: Journal of the Transportation Research Board* (forthcoming).
20. Das, S., S. Geedipally, K. Dixon, X. Sun, and C. Ma. Measuring the Effectiveness of Vehicle Inspection Regulations in Different States of the U.S. *Transportation Research Record: Journal of the Transportation Research Board* (forthcoming).
21. Das, S., A. Dutta, S. Geedipally, C. Ma, and Z Elgart. Effect of Vehicular Defects on Crash Severity: A Bayesian Data Mining Approach. Presented at 98th Annual Meeting of the Transportation Research Board, Washington, D.C., 2019.
22. Das, S., A. Dutta, R. Avelar, K. Dixon, X. Sun, and M. Jalayer. Supervised Association Rules Mining on Pedestrian Crashes in Urban Areas: Identifying Patterns for Appropriate Countermeasures. *International Journal of Urban Sciences*, Vol. 23, No. 1, 2018, pp. 1–19.
23. Das, S., L. Minjares-Kyle, R. Avelar, K. Dixon, and B. Bommanayakanahalli. Improper Passing-Related Crashes on Rural Roadways: Using Association Rules Negative Binomial Miner. Presented at 96th Annual Meeting of the Transportation Research Board, Washington, D.C., 2017.
24. Fontaine, H. *A Typological Analysis of Pedestrian Accidents*. Presented at the 7th workshop of ICTCT, Paris, France, 1995.
25. Das, S., A. Mudgal, A. Dutta, and S. Geedipally. Vehicle Consumer Complaint Reports Involving Severe Incidents: Mining Large Contingency Tables. *Transportation Research Record: Journal of the Transportation Research Board*, 2018. 2672(32): 72–82.
26. Factor, R, G. Yair, and D. Mahalel. Who by Accident? The Social Morphology of Car Accidents. *Risk Analysis*, Vol. 30, No. 9, 2010, pp. 1411–1423.
27. Das, S., R. Avelar, K. Dixon, and X. Sun. Investigation on the Wrong Way Driving Crash Patterns using Multiple Correspondence Analysis. *Accident Analysis and Prevention*, Vol. 111, 2018, pp. 43–55.
28. Das, S., B. K. Brimley, T. Lindheimer, and A. Pant. *Safety Impacts of Reduced Visibility in Inclement Weather*. No. ATLAS-2017-19. Center for Advancing Transportation Leadership and Safety (ATLAS Center), Ann Arbor, MI, 2017.
29. Das, S., and X. Sun. Association Knowledge for Fatal Run-off-Road Crashes by Multiple Correspondence Analysis. *IATSS Research*, Vol. 39, No. 2, 2016, pp. 146–155.
30. Das, S., and X. Sun. Factor Association with Multiple Correspondence Analysis in Vehicle–Pedestrian Crashes. *Transportation Research Record: Journal of the Transportation Research Board*, 2015. 2519: 95–103.
31. Baireddy, R., H. Zhou, and M. Jalayer. Multiple Correspondence Analysis of Pedestrian Crashes in Rural Illinois. *Transportation Research Record: Journal of the Transportation Research Board*, 2018. 2672(38): 116–127.
32. Das, S., A. Dutta, M. Jalayer, A. Bibeka, and L. Wu. Factors Influencing the Patterns of Wrong Way Driving Crashes on Freeway Exit Ramps and Median Crossovers: Exploration using "Eclat" Association Rules to Promote Safety. *International Journal of Transportation Science and Technology*, Vol. 7, No. 2 , 2018, pp. 114–123.
33. Jalayer, M., M. Pour-Rouholamin, and H. Zhou. Wrong-Way Driving Crashes: A Multiple Correspondence Approach to Identify Contributing Factors. *Traffic Injury Prevention*, Vol. 19, No. 1, 2018, pp. 35–41.

34. Das, S., X. Sun, F. Wang, and C. Leboeuf. Estimating Likelihood of Future Crashes for Crash-Prone Drivers. *Journal of Traffic and Transportation Engineering*, Vol. 2, No. 3, 2015, pp. 145–157.
35. Jalayer, M., H. Zhou, and S. Das. *Exploratory Analysis of Run-off-Road Crash Patterns*. Data Analytics for Smart Cities, CRC Press, Washington D.C., 2018.
36. NHTSA. *2016 FARS/CRSS Pedestrian Bicyclist Crash Typing Manual: A Guide for Coders using the FARS/CRSS Ped/Bike Typing Tool*. National Highway Traffic Safety Administration, Washington, D.C., 2018.
37. Vermunt, J. K., and C. J. Anderson. Joint Correspondence Analysis (JCA) by Maximum Likelihood. *Methodology*, Vol. 1, No. 1, 2005, pp. 18–26.
38. Nenadic, O., and M. Greenacre. Correspondence Analysis in R, with Two- and Three-Dimensional Graphics: The ca Package. *Journal of Statistical Software*, Vol. 20, No. 3, 2007, pp. 1–13.
39. Wickham, H. *ggplot2: Elegant Graphics for Data Analysis*. Springer-Verlag, New York, NY, 2009.
40. Slowikowski, K. *ggrepel: Repulsive Text and Label Geoms for "ggplot2." R package version 0.7.0*. 2017.
41. Helak, K., D. Jehle, D. McNabb, A. Battisti, S. Sanford, and M. C. Lark. Factors Influencing Injury Severity of Bicyclists Involved in Crashes with Motor Vehicles: Bike Lanes, Alcohol, Lighting, Speed, and Helmet Use. *Southern Medical Journal*, Vol. 110, No. 7, 2017, pp. 441–444.
42. Wang, C., L. Lu, and J. Lu. Statistical Analysis of Bicyclists' Injury Severity at Unsignalized Intersections. *Traffic Injury Prevention*, Vol. 16, No. 5, 2015, pp. 507–512.
43. Turner, S., I. Sener, M. Martin, S. Das, E. Shipp, R. Hampshire, K. Fitzpatrick, L. Molnar, R. Wijesundera, M. Colety, and S. Robinson. *Synthesis of Methods for Estimating Pedestrian and Bicyclist Exposure to Risk at Areawide Levels and on Specific Transportation Facilities*. Report No. FHWA-SA-17-041. Federal Highway Administration, Washington, D.C., 2017.
44. Lynott, J., J. Haase, K. Nelson, ASLA, A. Taylor, B. McCann, and E. R. Stollof. *Planning Complete Streets for an Aging America*. AARP Public Policy Institute, Washington, D.C., 2009.

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