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Analysis of factors that influence injury severity of single and multivehicle crashes involving at-fault older drivers: A random parameters logit with heterogeneity in means and variances approach

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A R T I C L E I N F O

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A B S T R A C T

The number of older drivers on our roads have been increasing given the upward shift of older people in the population. It is well-known that older drivers are more susceptible to injury given a crash. They are also likely to be at-fault in certain types of crashes due to health conditions associated with old age. This paper identifies factors that influence the severity of crashes involving at-fault older drivers at a disaggregated level for single and multivehicle crashes. Two random parameters multinomial logit with heterogeneity in means and variances models of injury severity were developed to assess the impact of various crash factors on crash outcomes based on the crash type. The study used five years of crash data from Alabama. The model estimations show that rainy weather and dark roadways were associated with an increased likelihood of serious injuries for single-vehicle crashes. Older male drivers were also found to have a higher probability of being at-fault in fatal single-vehicle crashes. For multivehicle older driver crashes, the model estimation results revealed that fatal injury was more likely to occur when the airbags were deployed. In addition, drivers between 65 and 75 years are less likely to be involved in fatal injury crashes for both single and multivehicle crashes. It was further found that older driver at-fault crashes that occurred in the open country were more likely to be fatal regardless of the manner of collision. The findings of this study are expected to help policymakers and transportation stakeholders to implement countermeasures that will make the road safer for older drivers and all other road users.

Introduction

Older drivers (65 years and above) are one of the vulnerable categories of drivers. Due to their declining health and frailty, crashes involving older drivers have higher chances of recording some form of injury as opposed to younger drivers. The National Highway Traffic Safety Administration, (2019) database showed that 7,214 older drivers were involved in fatal crashes in the U.S in 2019. This number is a 3 percent increase from 2018 and represents about 20 % of all fatal crashes in the U.S. The number of fatal crashes is significant considering that older people make up 16 % of the total population in America (National Highway Traffic Safety Administration, 2019). Perhaps, this may be because of age-related health conditions that affect their ability to successfully execute some driving tasks. Indeed, studies have found that as drivers grow older, their vision and cognitive skills decline, as well as their physical state, which ultimately affect driving performance (Centers for Disease Control and Prevention, 2022).

Due to the potential of injury in crashes involving older drivers, many studies have been carried out to understand the contributing factors and mechanisms of older driver crashes. For instance, Cicchino and McCartt, (2015) investigated crashes among 647 drivers aged 70 years and older and found that the common contributing factors were inadequate surveillance, misjudging the headway between vehicles, illegal maneuvers, and daydreaming. Consistent with these findings, Clarke et al., (2010) also determined from over 2,000 crashes that drivers over 60 years fail to yield the right of way at intersections. Older drivers were also found to have longer perception-reaction times at intersections. Braitman et al., (2007) observed that the older drivers get,

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the higher the probability that they will fail to yield that right of way at stop sign-controlled intersections. In addition, drivers between 70 and 79 years were found to make more errors evaluating whether they have adequate time to proceed than drivers between 35 and 54 years. Other crash contributing factors common among older drivers include fatigue, illness, and impairment caused by medications (Dobbs et al., 2005), unintended acceleration (Clarke et al., 2010), and poor contrast sensitivity (Horswill et al., 2008). Furthermore, in considering the manner of crash and vehicle maneuvers, rear-end crashes, left-turn movements, and ran-of-road were found to be common among older drivers (Mortimer and Fell, 1989; Mayhew et al., 2006; Lotfipour et al., 2013).

Regarding gender differences in crash involvement, older male drivers are more involved in crashes than female drivers. This difference has been attributed to female drivers being more cautious than male drivers (National Highway Traffic Safety Administration, 2019; Centers for Disease Control and Prevention, 2022). In addition, older drivers were also involved in more fatal crashes on rural roads than on urban roads (National Highway Traffic Safety Administration, 2019). As older drivers are aware of the risks associated with driving, they take actions such as driving fewer kilometers, avoiding driving at night, and limiting traffic peak hour driving (Langford and Koppel, 2006). These actions are supposed to reduce the number of crashes involving older drivers. However, research from Braitman et al., (2007), Clarke et al., (2010) and National Highway Traffic Safety Administration, (2019) have predicted an increase in the number of older drivers using the road in the future. This information makes it essential to study the factors associated with older driver crashes to identify priority emphasis areas for countermeasure development and implementation. Table 1 summarizes some more previous research on older drivers, methods used, and the key findings.

Table 1
Summary of methods used and findings in older drivers crash studies.

Author	Method	Findings
Kim et al. (2013)	Random parameters logit with heterogeneity in mean	Older drivers are associated with equal chances of both fatal and non-fatal crashes as compared to working-age groups.Crash involving older driver driving an older car has higher probability of recording fatal injury.
Adanu et al. (2021)	Random parameters logit with heterogeneity in means.	Older male drivers are less likely to be severely injured in lane-changing crashes as compared to younger male drivers. Older drivers are more likely to be involved in major injury crashesunder dark/unlit lighting conditions.
Boufous et al. (2008)	Univariate and multivariate linear regression.	Crashes occurring in rural areas are more severe and more likely to be fatal as compared to urban areas. Driving on roads with high-speed limits increases the likelihood of severe injuriesDriving under the influence of alcohol has no significant effect on increasing the likelihood of severe injuries in older drivers that were hospitalized.
Khattak et al. (2002)	Ordered probit model	Increasing driving age and the absence of safety equipment increase the likelihood of older driver injury severity. Male older drivers are more vulnerable to injuries than female older drivers. Severe injuries are associated with curves on level terrains. Crashes involving swerving animals are likely to be less severe.Crashes that occurred in rural areas and crashes under dark conditions are likely to be severe for older drivers.
Duddu et al. (2018)	Partial proportional odds model	At-fault drivers older than 70 years are 2.59 times more likely to be involved in severe injuries when involved in crashes as compared to At-fault drivers between 26 and 40 years. At-fault driver age and not at-fault driver age have no significant effect on each other.

The primary contributing factors of multivehicle crashes are typically attributed to one of the drivers. In the case of single-vehicle crashes, the driver is considered as the causal unit as the influence of any other vehicle may either be minimal or absent. The crash mechanisms and factors associated with injury outcomes are therefore more likely to be different between single- and multivehicle crashes even though the causal unit type may be the same (Islam et al., 2014). Hence, analyzing a full crash dataset without accounting for some fundamental differences in the data could conceal certain vital information that may be important for the development of appropriate and targeted countermeasures. According to Morgan and Mannering, (2011) this disaggregate approach to analyzing crash data helps to uncover unobserved patterns that may be lost when the data is not segmented. While previous older driver crash studies have helped to identify many different factors that correlate with crash outcomes, there has not been much research that compares single and multivehicle crashes involving at-fault older drivers. Most previous research also failed to account for unobserved heterogeneity associated with crash data involving only older drivers. The few studies that accounted for unobserved heterogeneity in older driver crash data only used older drivers as a variable in their study (Kim et al., 2013; Adanu et al., 2021). This research was undertaken to fill these gaps and to investigate whether factors associated with crash outcomes differ between single- and multivehicle crashes involving at-fault older drivers. Separate crash severity models were therefore adopted to understand the similarities and differences in injury contributing factors based on the crash mechanism. The sections below describe the crash data, methodology, results and discussions, conclusions, and future research plans.

Data description

Crash data for at-fault older drivers (65 years and older) in Alabama were filtered from the Critical Analysis Reporting Environment (CARE) software system developed by the University of Alabama Center for Advanced Public Safety (CAPS) for the period covering 2014 to 2018. This yielded a total of 70,975 crashes. For the purposes of this study, the data was further filtered to select only injury-related crashes (i.e., crashes that resulted in fatal injury, suspected serious injury, and suspected minor injury). After data cleaning efforts, a total of 8,681 crashes were available for analysis. The data was then divided into single (2,436 observations) and multivehicle (6,245 observations) crashes. Preliminary analysis (Fig. 1) of the data revealed that single and multivehicle injury-related crashes increased by 18.1 % and 20.9 %, respectively from 2014 to 2017. However, from 2017 to 2018, single vehicle crashes reduced by 1.1 % and multivehicle crashes reduced by 3.3 %.

With respect to injury outcomes, 8.3 % of the single-vehicle crashes were fatal, 35.6 % were suspected serious injury and 56.2 % were suspected minor injury crashes. Ran-off-the-road was the primary contributing circumstance in about 17.2 % of the single-vehicle crashes. Driver fatigue (11.8 %), driving too fast for road conditions (7.5 %), swerving to avoid vehicles (4.5 %), and DUI (4.45 %) were other major primary contributing factors associated with older drivers single-vehicle crashes. Regarding the location of crashes, 31.6 % of single-vehicle older driver crashes occurred at intersections whiles the remaining 68.4 % occurred at non-intersections. Crashes occurring in open countries were 65.3 % whiles residential and business/shopping areas were 20.8 % and 11.9 %, respectively. Drivers between 65 and 75 years accounted for 70.1 % of the single vehicle crashes whiles drivers older than 75 years

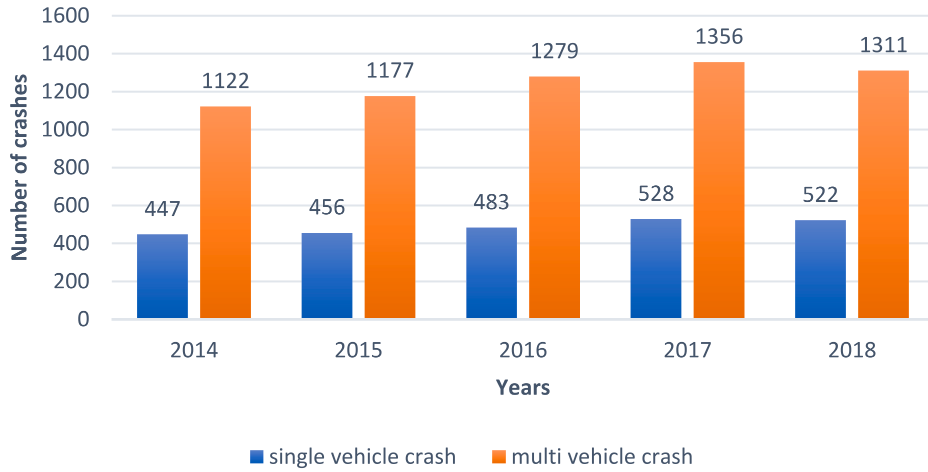

Fig. 1. Single and multivehicle crashes (2014–2018).

constituted 29.9 %.

For multivehicle older drivers at-fault crashes, 4.7 % were fatal, 31.5 % were suspected serious injury injuries and 63.8 % were suspected minor injury. Unlike single-vehicle crashes, most multivehicle crashes were located at intersections (68.4 %) whiles the significant primary contributing factors were failure to yield the right of way (48.5 %), running traffic signals (7.5 %), running stop signs (2.6 %) and misjudging stopping distance (6.1 %). For the manner of crash, side-impact (90 degrees) and side-impact (angled) represented 31.9 % and 19 % respectively. Rear end collision also accounts for 23.1 % of all crashes. The higher number of angular crashes as compared to rear-end crashes mirrors the finding from Yasmin et al. (2014) that older drivers have relatively slower reactions and are unable to complete turning actions quickly resulting in angular crashes. Other manner of crashes was head-on collision (6.2 %) and angled oncoming frontal collisions (6.9 %). In comparison to single-vehicle crashes, most crashes occurred in shopping/business areas (47.4 %) whiles crashes in open country made up 34.2 % of total crashes. Drivers between the age of 65 and 75 years were 59.6 % of the total older driver at-fault multivehicle crashes while 40.4 % were above 75 years. The descriptive statistics of the crash variables are summarized in Table 2.

Methodology

Road crashes are complex events involving multifactorial circumstances associated with interactions between humans with vehicles, roadways, traffic, and the environment (Lord et al., 2021; Mannering et al., 2016). Due to this complexity, many factors associated with the crash remain unknown and police officers who are primarily tasked to record crashes are often unable to document all crash factors in a standard crash report. Consequently, results obtained from analyzing historical crash data using traditional statistical modeling techniques may be erroneous and the inferences made from them maybe biased towards the development of countermeasures for variables that are reported in the crash form and used for the analysis. To address these limitations which is referred to as unobserved heterogeneity, advanced statistical models such as random (ordered and unordered) logit (Eluru and Bhat, 2007; Eluru et al., 2008; Christoforou et al., 2010; Paleti et al., 2010; Xiong and Mannering, 2013) and latent class finite mixture models (Adanu et al., 2018, 2021, 2023; Behnood et al., 2014; Behnood and Mannering, 2016) are generally used.

This study used mixed logit model with heterogeneity in means and variance across crash observations to account for unobserved heterogeneity (Islam et al., 2014; Yan et al., 2021; Behnood and Mannering, 2017; Seraneeprakarn et al., 2017; Adanu et al., 2023; McFadden et al., 1981). Three crash outcomes were considered for this study namely: Fatal injury (K), Suspected serious injury (A), and Suspected minor injury (B). In developing the model, injury severity function S_{in} was used to determine the probability that crash n will result in injury i (McFadden et al., 1981), as Eqn 1:

$$S_{in} = \beta_i X_{in} + \varepsilon_{in} \tag{1}$$

Where $\beta_{\mathbf{i}}$ is a vector of parameter estimates to be determined for crash outcome i (Fatal, suspected serious injury, and suspected minor injury injury), $\mathbf{X_{in}}$ is a vector of explanatory variables that affect the likelihood of injury outcome i in crash n and ε_{in} is the stochastic error term. If ε_{in} is assumed to follow an independent and identically distributed extreme value Type I distribution (Manski and McFadden, 1981), and parameter variations across observations are allowed for by introducing a mixing distribution (McFadden and Train, 2000) the resulting mixed logit model is:

$$P_n(i) = \int \frac{\exp\beta_i X_{in}}{\sum_{\forall i}\exp(\beta_i X_{in})} f(\beta|\varphi) d\beta \tag{2}$$

Where $f(\beta|\varphi)$ is the density of β and φ corresponding to a vector of parameters of the density function (mean and variance), $P_n(i)$ is the probability of crash severity i in crash n conditional on $f(\beta|\varphi)$. With this formulation, β can now account for observation-specific variations in the effect of $\mathbf{X}$ on crash outcome probabilities, with $f(\beta|\varphi)$ used to determine β**.** The mixed-logit probabilities then become the weighted average for different values of β across observations where some elements of β may be fixed across observations and some may vary across observations (known as random parameters). Due to the difficulty in estimating the parameters of the mixed logit model, the model is often estimated by simulated maximum likelihood estimation with the logit probabilities (shown in Eqn 3) approximated by drawing values of β from $f(\beta|\varphi)$ for given values of φ, using Halton draws (Bhat, 2003; Halton, 1960). Halton draws have previously been shown to do a better job than random draws. Heterogeneity in means and variances of random parameters is accounted for by allowing β_i to vary across crashes as (Adanu et al., 2023; Washington et al., 2020):

$$\beta_i = \beta + \Theta_i \mathbf{Z}_i + \sigma_i \exp(\omega_i \mathbf{W}_i) \upsilon_i \tag{3}$$

where β is the mean parameter estimate across all crashes, $\mathbf{Z}_i$ is a vector of attributes that capture heterogeneity in the mean, Θ_i is a corresponding vector of estimable parameters, $\mathbf{W}_i$ is a vector of attributes that capture heterogeneity in standard deviation σ_i with corresponding parameter vector ω_i and a disturbance term υi, and $\mathbf{Z_i}$ and $\mathbf{W_i}$ may contain crash attributes or other sources of heterogeneity that may not be captured by variables recorded in the crash database.

Marginal effects were further estimated to assess the effect of the

Table 2
Summary statistics of older drivers crash variables.

Variable		Single vehicle Frequency (%)	Multivehicle Frequency (%)
Crash severity	Fatal (K)	201 (8.3 %)	292 (4.7 %)
	Suspected serious injury (A)	866 (35.6 %)	1969 (31.5 %)
	Suspected minor injury (B)	1369 (56.2 %)	3984 (63.8 %)
Year			
	2014	447 (18.3 %)	1122 (18.0 %)
	2015	456 (18.7 %)	1177 (18.8 %)
	2016	483 (19.8 %)	1279 (20.5 %)
	2017	528 (21.7 %)	1356 (21.7 %)
	2018	522 (21.4 %)	1311 (21.0 %)
Primary contributing factors			
	Failed to yield right of way	–	3028 (48.5 %)
	Others	1140 (46.7 %)	1479 (23.7 %)
	Vision obstructed	–	56 (0.9 %)
	Unseen object/person/vehicle	86 (3.5 %)	232 (3.7 %)
	Swerved to avoid vehicles	109 (4.5 %)	48 (0.8 %)
	Swerve to avoid animal	61 (2.5 %)	–
	Ran traffic signal	–	469 (7.5 %)
	Ran stop sign	30 (1.2 %)	164 (2.6 %)
	Overspeed limit	–	22 (0.4 %)
	Misjudge stopping distance	–	380 (6.1 %)
	Made improper turn	14 (0.6 %)	
	Improper lane change	–	159 (2.5 %)
	Fatigued/Asleep	288 (11.8 %)	62 (1.0 %)
	DUI	107 (4.4 %)	81 (1.3 %)
	Ran off the road	419 (17.2 %)	–
	Driving too fast for the condition	182 (7.5 %)	65 (1.0 %)
Manner of crash			
	Head-on	–	387 (6.2 %)
	Angle oncoming (frontal)	–	431 (6.9)
	Angle (front to side) same direction	–	155 (2.5 %)
	Angle (front to side) opposite direction	–	368 (5.9 %)
	Rear end (front to rear)	–	1441 (23.1 %)
	Side Impact (angled)	–	1061 (17.0 %)
	Side impact (90 degrees)	–	1994 (31.9 %)
	Side swipe - same direction	–	174 (2.8 %)
	Side swipe-opposite direction	–	101 (1.6 %)
	Others	–	133 (2.1 %)
Intersection			
	Yes, the crash occurred at an intersection	770 (31.6 %)	4271 (68.4 %)
	No, the crash did not occur at an intersection	1666 (68.4 %)	1961 (31.4 %)
	Unknown	–	13 (0.2 %)
Lighting condition			
	Daylight	1817 (74.6 %)	5169 (82.8 %)
	Dusk	46 (1.9 %)	167 (2.7 %)
	Dawn	25 (1.0 %)	56 (0.9 %)
	Dark	543 (22.3 %)	850 (13.6 %)

Table 2 (*continued*)

Variable		Single vehicle Frequency (%)	Multivehicle Frequency (%)
Crash severity	Fatal (K)	201 (8.3 %)	292 (4.7 %)
	Others	5 (0.2 %)	3 (0.0 %)
Weather			
	Rain	247 (10.1 %)	418 (6.7 %)
	Mist	41 (1.7 %)	117 (1.9 %)
	Cloudy	520 (21.3 %)	1212 (19.4 %)
	Clear	1593 (65.4 %)	4450 (71.3 %)
	Others	22 (0.9 %)	48 (0.8 %)
Local			
	Open country	1591 (65.3 %)	2133 (34.2 %)
	Residential	506 (20.8 %)	952 (15.2 %)
	Shopping or business	289 (11.9 %)	2960 (47.4 %)
	Others	50 (2.1 %)	200 (3.2 %)
Driver Race			
	White/Caucasian	1974 (81.0 %)	5080 (81.3 %)
	Black/African American	440 (18.1 %)	1099 (17.6 %)
	Hispanic	9 (0.4 %)	20 (0.3 %)
	Others	13 (0.5 %)	46 (0.7 %)
Driver gender			
	Male	1569 (64.4 %)	3439 (55.1 %)
	Female	867 (35.6 %)	2802 (44.9 %)
	Others/Unknown	–	4 (0.1 %)
Driver Employment status			
	Employed	362 (14.9 %)	940 (15.1 %)
	Unemployed	345 (14.2 %)	636 (10.2 %)
	Self-employed	91 (3.7 %)	201 (3.2 %)
	Retired	1291 (53.0 %)	3450 (55.2 %)
	Others	347 (14.2 %)	1018 (16.3 %)
Driver condition			
	Physical Impairment	64 (2.6 %)	59 (0.9 %)
	Illness	228 (9.4 %)	97 (1.6 %)
	Asleep	269 (11.0 %)	88 (1.4 %)
	Apparently normal	1482 (60.8 %)	5592 (89.5 %)
	Others	271 (11.1 %)	409 (6.5 %)
Vehicle maneuvers			
	Turning right	47 (1.9 %)	193 (3.1 %)
	Turning left	62 (2.5 %)	1885 (30.2 %)
	Movement essentially straight	1679 (68.9 %)	3056 (48.9 %)
	Entering the main road	15 (0.6 %)	388 (6.2 %)
	Changing lanes	11(0.5 %)	160 (2.6 %)
	Backing	16 (0.7 %)	38 (0.6 %)
	Others	606 (24.9 %)	525 (8.4 %)
Airbag status			
	Airbag not deployed	1008 (41.4 %)	3005 (48.1 %)
	Airbag deployed	1066 (43.8 %)	2755 (44.1 %)
	Others	362 (14.9 %)	485 (7.8 %)
Road conditions			
	Dry	1928 (79.1 %)	5462 (87.5 %)

(*continued on next page*)

Table 2 (*continued*)

Variable		Single vehicle Frequency (%)	Multivehicle Frequency (%)
Crash severity	Fatal (K)	201 (8.3 %)	292 (4.7 %)
	Wet	407 (16.7 %)	720 (11.5 %)
	Others	101 (4.1 %)	63 (1.0 %)
Opposing lane separation			
	Unpaved surface	345 (14.2 %)	1162 (18.6 %)
	Solid painted lines	1252 (51.4 %)	3105 (49.7 %)
	Broken Painted line	297 (12.2 %)	462 (7.4 %)
	Others	69 (2.8 %)	1516 (24.3 %)
Number of lanes			
	One or two lanes	1721 (70.6 %)	3016 (48.3 %)
	More than 2 lanes	715 (29.4 %)	3229 (51.7 %)
Roadway curvature/grade	Straight (level, downgrade, upgrade, hillcrest)	1600 (65.7 %)	5835 (93.4 %)
	Curve	767 (31.5 %)	356 (5.7 %)
	Others	69 (2.8 %)	54 (0.9 %)
Driver age			
	65–75 years	1709 (70.1 %)	3720 (59.6 %)
	> 65	727 (29.9)	2525 (40.4 %)

crash-contributing factors on the likelihood of crash-severity outcomes (Washington et al., 2020). In this study, all the explanatory variables are coded as indicator variables. As such, the marginal effects are calculated as Eqn 4:

$$\mathrm{ME}_{\mathrm{X}_{\mathrm{ijk}}}^{\mathrm{P}_{\mathrm{ij}}} = \mathrm{P}_{\mathrm{ij}}\left(\mathbf{X}_{\mathrm{ijk}} = 1\right) - \mathrm{P}_{\mathrm{ij}}\left(\mathbf{X}_{\mathrm{ijk}} = 0\right) \tag{4}$$

The probabilities specific to each severity level i for crash j, are calculated when the k^{th} indicator variable, $\mathrm{X}_{\mathrm{ijk}}$ which equals 1 or 0, respectively. Specifically, a marginal effect for $\mathbf{X}_{\mathrm{ijk}}$ is the difference in probabilities when $\mathbf{X}_{\mathrm{ijk}}$ changes from 0 to 1 while all other variables remain constant. For variables with random parameters across all observations, only the estimated mean value of the coefficients is used in the utility function to calculate the marginal effects. The marginal effect for each parameter is calculated by averaging the marginal effects of overall crash observations. For model estimation, the NLOGIT 6.0 was used. This software contains a set of tools for building discrete choice models by supporting both discrete and continuous variables (Greene, 2012)

Transferability test

Transferability tests were conducted to investigate whether separate models were needed to understand the effects of various crash factors on crash outcomes across crash types (single and multivehicle). For assessing parameter transferability, the test statistic used is Eqn 5:

$$X^2 = -2\left[LL(\boldsymbol{\beta}_T) - \sum_{k=1}^{K} LL(\boldsymbol{\beta}_k)\right], \tag{5}$$

where $LL(\boldsymbol{\beta}_T)$ is the log-likelihood at convergence of the model estimated with all the data, $LL(\boldsymbol{\beta}_k)$ is the log-likelihood at convergence of the model using subset k data (single-vehicle and multivehicle) and K is the total number of data subsets used. The X^2 statistic is chi-squared distributed with degrees of freedom equal to the sum of the number of estimated parameters in all subset models minus the number of estimated parameters in the full-sample model. The resulting X^2 statistic indicates whether the model for the subset data is significantly different than the model for the full sample data. Log-likelihood test was further performed to determine whether the subset models have parameters that are statistically different. The test statistic used is given by Eqn 6:

$$X^2 = -2[LL(\boldsymbol{\beta}_T) - LL(\boldsymbol{\beta}_k)], \tag{6}$$

where $LL(\boldsymbol{\beta}_T)$ is the log-likelihood at convergence of the model estimated with all the data, $LL(\boldsymbol{\beta}_k)$ is the log-likelihood at convergence of the model using subset k data. The results obtained are $X^2 = 44.16546$ and a degree of freedom of 15. A resulting p-value of 0.9999 indicated that the null hypothesis that the two models are the same can be rejected at 99.99 % confidence level.

Model estimation results and discussions

Tables 3 and 4 show the estimated results for the single and multivehicle older drivers at-fault crashes. The models were estimated using the maximum likelihood approach with 1500 Halton draws. The McFadden Pseudo ρ^2 for the single-vehicle model was 0.22 whiles multivehicle model ha ρ^2 of 0.3. The indicator variables for “Clear weather” and “Intersection” were found to produce random parameters in the single and multivehicle crash models, respectively. The normal distribution provided the best fit for the random variables.

For the single-vehicle model, the clear weather variable (defined for the suspected serious injury function) was found to be random with mean of -0.669 and a standard deviation of 4.006. This result indicates that for 43.36 % of clear weather crashes that involve single vehicles, there was a higher probability of suspected serious injury. For the remaining 56.64 % of clear weather crashes, the probability of suspected serious injury is low. The indicator variables for ‘intersection’ and ‘ran stop sign or traffic signal’ increased the heterogeneity in the mean of the ‘clear weather’ random variable. This revealed that clear weather crashes at intersections and those that involve running a stop sign or traffic signal were more likely to record serious injuries. Concerning heterogeneity in variance, the ‘urban’ indicator produced a significant heterogeneity in the variance of the ‘clear weather’ random variable. This variable had a decreasing effect on the variance of the ‘clear weather’ variable, indicating that single-vehicle crashes involving older drivers in urban areas under clear weather conditions were less likely to record serious injuries. The marginal effects show that the clear weather indicator increased the likelihood of suspected serious injury by 0.0285 and decreased the probability of fatal injury outcome and suspected minor injury by 0.0034 and 0.0251, respectively.

For the multivehicle model, the intersection variable (defined for suspected minor injury) was random with a mean of 0.577 and a standard deviation of 5.044. On the normal distribution curve, these numbers indicate that for 54.55 % of intersection crashes that involve multivehicles, there was a higher probability of suspected minor injury. For the remaining 45.45 % of intersection crashes, the probability of suspected minor injury is low. The variable, “ran stop sign or traffic signal” was found to significantly decrease the heterogeneity in mean of the intersection random parameter making suspected minor injury less likely while the variable for crash time between ‘7:00 am and 9:00 am’ increased the mean of the intersection random parameter. This indicates that intersection-related crashes that occur between 7:00 am and 9:00 am were more likely to record minor injury. This finding may perhaps be due to the chances of lower speeds at intersections because of higher traffic volumes during the morning peak hours. Also, the ‘urban’ indicator variable was found to produce a significant heterogeneity in the variance of the intersection random variable. Results from the marginal effects indicate that the intersection indicator increases the likelihood of suspected minor injury by 0.002 and decrease the probability of fatal injury and suspected serious injury by 0.0008 and 0.0012, respectively.

Table 3
Severity model results and averaged marginal effects for single vehicle crash.

Variables	In Injury function of:	Parameter estimates	t-statistics	Marginal effect K	A	B
Constant	Suspected minor injury	2.38214	8.79			
Random Parameter						
Clear weather	Suspected serious injury	−0.66988	−1.97	−0.0034	0.0285	−0.0251
Standard deviation “Clear weather” (Normally distributed)		4.00592	3.11			
Heterogeneity in means						
Clear weather: At Intersection		0.5341	1.74			
Clear weather: Ran stop/signal		1.83877	1.79			
Heterogeneity in variance						
Clear weather: Urban		−0.69323	−2.7			
Crash Characteristics						
Swerve to avoid vehicle/object/non-motorist/animal	Fatal	−1.70314	−3.26	−0.0027	0.0006	0.0021
No airbag deployed	Suspected minor injury	0.25699	2.42	−0.0072	−0.016	0.0231
Driver Characteristics						
Male	Fatal	0.80161	4.33	0.0452	−0.0116	−0.0336
Asleep	Fatal	−1.5467	−3.89	−0.0044	0.0009	0.0034
Ill	Suspected serious injury	0.51642	2.46	−0.0011	0.0071	−0.006
Physically impaired	Suspected serious injury	1.42972	3.79	−0.0008	0.0058	−0.0051
Retired	Suspected minor injury	0.31232	2.64	−0.0089	−0.02	0.0288
Employed	Suspected minor injury	0.66755	3.95	−0.0048	−0.0114	0.0162
Driver age (65–75 years)	Suspected serious injury	0.32766	2.46	−0.0045	0.0327	−0.0282
Race: Hispanic	Suspected serious injury	1.82403	1.82	−0.0002	0.0009	−0.0008
Race: White	Suspected serious injury	0.37845	2.5	−0.0058	0.0433	−0.0375
Environmental Characteristics						
Rain	Fatal	−0.88773	−2.78	−0.0041	0.0015	0.0026
Day light	Suspected serious injury	1.39683	5.95	−0.0195	0.1478	−0.1284
Dark	Suspected serious injury	1.30757	5.07	−0.0058	0.0408	−0.0351
Land use characteristics						
Open country	Fatal	0.57726	2.98	0.0321	−0.0084	−0.0236
Residential	Suspected minor injury	0.39029	2.63	−0.003	−0.0105	0.0135
Roadway Characteristic						
Broken painted line	Suspected serious injury	0.45486	2.4	−0.0011	0.0082	−0.0072
Not at Intersection	Suspected minor injury	−0.56616	−4.28	0.0236	0.0468	−0.0704
Roadway curvature: Straight	Suspected minor injury	0.24928	2.25	−0.0082	−0.0198	0.028
Model Statistics						
Number of Observations	2436					
Log-likelihood at constants	−2676.22					
Log-likelihood at convergence	−2087.11					
McFadden Pseudo r squared	0.22					

The marginal effects of crash variables influencing injury outcomes have also been shown in Tables 3 and 4. The variables are accordingly grouped in various thematic areas and discussed in the next section.

Crash characteristics

Various crash characteristics have been found to significantly influence older driver injury severity. For instance, it was found that single-vehicle crashes involving swerving to avoid a vehicle/animal/object/non-motorist were more likely to record a minor injury. The marginal effects show that the swerving to avoid collision variable increased the probability of suspected minor injury by 0.002 and the likelihood of fatal and serious injuries was lower. Also, the variable for ‘no airbag deployed’ increased the probability of suspected minor injury and reduced the probability of fatal injury by 0.0072 and suspected serious injury by 0.016 for single-vehicle crashes. This observation can be seen from three angles. Firstly, airbags are usually deployed when speed at impact is relatively high. This means that higher speed at impact can be linked to airbag deployment and a higher injury severity. However, non-deployment of airbags might likely mean the speed at impact is relatively low and hence the likelihood of less severe injury. On the other hand, studies by (Awadzi et al., 2008; Jernigan and Duma, 2003) also revealed that older drivers are susceptible to injuries because of forces generated to the chest area by airbags deployment resulting in more severe injury. Finally, it is possible that no airbag was deployed in the crashes because there was no airbag installed in the vehicle. The conflicting results from airbags deployment, injury severity and older drivers need further investigation.

For multivehicle crashes, the deployment of airbags was found to increase the probability of fatal injury by 0.0042 and decrease the likelihood of suspected serious and suspected minor injuries. This finding is consistent with findings in some previous studies (e.g., Awadzi et al., 2008; Jernigan and Duma, 2003). Considering the manner of collision, it was found that angled collision, rear end, and sideswipe crashes were likely to result in suspected serious injury while side-impacts and head-on collisions were more likely to result in fatal and suspected serious injuries. In terms of vehicle movements, misjudging stopping distances and backing maneuvers were more likely to result in suspected minor injury. These findings are consistent with those from other previous studies (Alam and Spainhour, 2008; Braitman et al., 2007; McGwin and Brown, 1999) which also demonstrated that older drivers are more likely to misjudge the speeds of other vehicles in traffic.

Driver characteristics

Considering the characteristics of the older drivers at-fault, the significant variables common to both single and multivehicle crashes are employed, retired, and drivers aged (65–75 years). The marginal effects indicate that employed and retired drivers increase the likelihood of suspected minor injury by 0.0162 and 0.0288 respectively in the single-vehicle model and respectively increase the probability of suspected minor injury by 0.0032 and 0.0103 in the multivehicle crash model. The variable for age group ‘65-70′ was found to increase the probability of suspected serious injury outcome by 0.0327 and 0.0065 for single and multivehicle crashes, respectively. From the two models, it was observed that the likelihood of a fatal injury outcome for crashes involving drivers

Table 4
Severity model results and averaged marginal effects for multivehicle crash.

Variables	In Injury function of:	Parameter estimates	t-statistics	Marginal effect		
				K	A	B
Constant	Suspected minor injury	1.139	9.41			
Random Parameter						
Intersection	Suspected minor injury	0.577	3.08	−0.0008	−0.0012	0.002
Standard deviation "Intersection" (Normally distributed)		5.043	2.84			
Heterogeneity in means						
Intersection: Ran stop/signal		−0.368	−2.44			
Intersection: Morning Peak (7:00am −9:00 am)		0.300	1.66			
Heterogeneity in variances						
Intersection: Urban		−1.213	−3.74			
Crash Characteristics						
Airbag deployed	Fatal	0.370	2.63	0.0042	−0.0021	−0.0021
Angled collision (frontal, front to side - same and opposite direction)	Suspected serious injury	0.722	5.01	−0.0018	0.0178	−0.0161
Rear end (front to rear)	Suspected serious injury	0.627	4.61	−0.0021	0.0246	−0.0225
Side swipe (same and opposite direction)	Suspected serious injury	0.609	3.22	−0.0005	0.0049	−0.0044
Side Impact (angled and 90 degrees)	Suspected minor injury	−0.680	−5.07	0.008	0.0429	−0.0509
Head on (front to front only)	Suspected minor injury	−1.145	−6.41	0.0023	0.0106	−0.0129
Misjudge Stopping Distance	Suspected minor injury	0.487	2.97	−0.0004	−0.004	0.0044
Backing	Suspected minor injury	1.873	2.89	−0.0002	−0.0006	0.0008
Driver Characteristics						
Employed	Fatal	−0.851	−4.44	−0.0067	0.0035	0.0032
Retired	Fatal	−0.896	−7.06	−0.0226	0.0122	0.0103
Female	Fatal	−0.749	−5.8	−0.0104	0.0055	0.0049
Unemployed	Suspected serious injury	0.324	2.98	−0.0015	0.0065	−0.005
Driver age (65–75 years)	Fatal	−0.530	−4.29	−0.0123	0.0065	0.0057
Environmental Characteristics						
Clear weather	Suspected serious injury	0.289	4	−0.0048	0.0341	−0.0293
Land use characteristics						
Open Country	Fatal	0.657	5.17	0.0154	−0.0093	−0.0061
Residential	Suspected minor injury	0.525	4.46	−0.0016	−0.0109	0.0124
Shopping or Business	Suspected minor injury	0.465	5.27	−0.0039	−0.0328	0.0368
Roadway Characteristics						
Number of lanes > 2	Fatal	−0.292	−2.29	−0.0053	0.0025	0.0027
Solid painted lines	Suspected serious injury	0.324	4.31	−0.0043	0.0264	−0.0221
Unpaved surfaces	Suspected serious injury	0.470	4.8	−0.0018	0.0155	−0.0138
Vehicle Characteristics						
Mini Van	Fatal	−1.041	−2.49	−0.0009	0.0005	0.0004
SUV	Suspected minor injury	0.223	2.45	−0.0009	−0.0061	0.007
Model Statistics						
Number of Observations	6245					
Log-likelihood at constants	−6860.83					
Log-likelihood at convergence	−4801.85					
McFadden Pseudo r squared	0.30					

between 65 and 75 years is low.

For significant crash variables peculiar to only single-vehicle crashes, it was found that older male drivers were more likely to be involved in fatal injury outcome crashes compared to their female counterparts. This is consistent with findings from Khattak et al. (2002). This could be because male drivers in general are more likely to take more risks during driving than female drivers. In addition, drowsy driving was found to be associated with increases in the probability of suspected serious and minor injuries by 0.0009 and 0.0034, respectively. Furthermore, crashes involving drivers that were identified as ill and physically impaired were more likely to record suspected serious injury and less likely to record fatal or suspected minor injury. Similarly, in considering the driver's race for the single-vehicle crashes model, the marginal effects show that the likelihood of suspected serious injury increased by 0.0433 and 0.0009 respectively for Caucasians and Hispanics. Regarding multi-vehicle crashes, female drivers were observed to less likely be involved in fatal injury whiles unemployed drivers were more likely to be involved in suspected serious injury.

Environmental characteristics

Whereas rain, daylight, and dark roadway conditions were significant crash variables associated with single-vehicle crashes, clear weather was significantly associated with multivehicle crashes. Again, using the marginal effects, the rain indicator reduced the probability of fatal injury by 0.0041while the likelihood of suspected serious and minor injuries was higher for single-vehicle crashes. This could be because older drivers usually drive carefully or drive less miles when raining. On the other hand, the clear weather indicator increased the probability of suspected serious injury for multivehicle crashes by 0.0341 while the likelihood of fatal and suspected minor injury was lower. As shown in literature that older drivers limit driving in the dark, the dark lighting condition indicator was found to increase the probability of suspected serious injury by 0.0408 in the single-vehicle crash model. This result is also consistent with findings from Adanu et al. (2021). Encouraging the use of night vision devices like infrared illuminator will help improve vision for older drivers who lose some of their ability to see low contrast objects at night. In addition, daylight indicator increased the likelihood of suspected serious injury outcome while the probability of fatal and suspected minor injuries was lower for single vehicle crash. Older drivers with vision problems tend to suffer more from glares during sunrise and sunset compared to younger drivers (David and Mike, 2007). This is because as drivers get older, the eye's pupil gets weak and shrinks. The glares from the sun on the weak pupil makes it difficult for older drivers to see what is ahead of them and hence increase their risk when driving. Considering that roadway lighting condition affects older drivers' crash risks, they should be educated to avoid driving in the direct direction of sunrise or sunset. Also, older drivers should be encouraged to frequently check their eyes to ensure that their vision is not an impediment to their driving activities.

Land use characteristics

Various locational attributes were assessed to understand their relationships with older drivers' injury risks. It was found that crashes that occur in the open country have a higher probability of resulting in fatal injury irrespective of the manner of collision. The marginal effects indicate that the open country variable increases the probability of fatal injury by 0.0321 and 0.0154 for single and multivehicle, respectively. From past studies, the presence of low traffic volumes on open country roads compared to urban areas leads to high-speed activities which might lead to fatal injury. In addition, longer distances from health facilities, bad network coverage and less chance of help from nearby drivers exacerbate injury severity in open country crashes (Chevalier et al., 2016; Khattak et al., 2002). In contrast, both single and multivehicle crashes that occur in residential areas were more likely to result in suspected minor injury. This may be due to the relatively lower speed limits in residential areas. Similarly, the indicator variable for crashes that occurred in shopping or business areas increased the probability of suspected minor injury by 0.0368 while the likelihood of fatal and serious injuries is lower for multivehicle crashes. Shopping and business areas typically have high volume of vehicles traveling at lower speeds with relatively smaller clearance. Also, shopping areas are often characterized by a high density of intersections. As older drivers are known to have relatively slower reaction times or increased decision times, they are likely to be involved in crashes. However, due to the slower speeds, these crashes tend to mostly be fender benders or suspected minor injury crashes. Even though these crashes might not be severe, damage to the vehicles worsen the financial burden on older drivers, particularly those that are unemployed. As a policy countermeasure public transportation should be made available older drivers incentivized to use them instead of driving to shopping and commercial areas. Major shopping centers could also allocate "seniors only" times, preferably during off-peak hours, to allow older people to come in and shop at those stipulated times. Also, older drivers should be encouraged to acquire vehicles equipped with advanced driver assist systems (ADAS) such as technologies for lane departure warning, collision warning and avoidance systems.

Roadway characteristics

The nature of the roadway plays an important role in the occurrence of crashes. In this study, roads with broken painted lines were more likely to record suspected major injury in single-vehicle crashes. It was also found that non-intersection single vehicle crashes had an increased probability of fatal injury outcome. The non-intersection variable increased the probability of fatal injury and serious injury by 0.0236 and 0.0468, respectively. This finding could be due to higher speed limits associated with non-intersections compared to intersections. Furthermore, single vehicle crashes that occurred on a straight road were more likely to record suspected minor injury.

For the multivehicle crash model, the indicator variable for the number of lanes greater than 2 reduced the likelihood of fatal injury and increased the probability of the lower injury severity categories. This is observation corroborates findings from Adanu et al. (2021) who found that the probability of major injury increases for older drivers overtaking on a two-lane road. Other significant variables like solid painted lines and unpaved surfaces (opposing lane separation) were found to be associated with a high probability of suspected serious injury.

Vehicle characteristics

Vehicles can provide some level of protection for drivers in the event of a crash. The characteristics of vehicles are particularly important determinants of injury in older drivers. In this study, indicator variables for minivans and SUVs were statistically significant in the multivehicle crash model. These variables were found to be associated with lower likelihood of fatal injury outcome. These vehicles better protect drivers involved in various type of crashes and this finding is consistent with findings from Kockelman and Kweon, (2002). Equipping vehicles with the necessary devices helps to cater for some of the special needs of older drivers to reduce the risk that comes with driving among older drivers. For instances, due to the fragile physical conditions of older drivers, vehicle manufacturers can reduce the force that are generated by airbags for older drivers to protect but also reduce the injuries generated when deployed. Newer technologies, such as advanced infotainment systems in cars, should be designed to be easy to use so as not to create unintended safety problems like being overwhelmed or distracted when operating them whiles driving.

To better understand how the significant crash variables common to both single and multivehicle models compare, Table 5 was constructed. From Table 5, it can be observed that the effects of many of the variables on crash outcomes did not differ significantly across crash types. For instance, the effects of all the common variables on fatal injury outcome was the same for both models. This means that irrespective of the manner of collision, older driver crashes that occurred under clear weather condition and involves drivers who are retired or employed are less likely to be fatal. However, open country crashes involving older drivers are likely to record fatalities regardless of whether the crashes are single-vehicle or involve multiple vehicles. In contrast, variables for retired, employed, and residential area crashes exhibited some differences in how they influence serious injury. This study found that while these variables had a negative association with serious injury outcome in single-vehicle crashes, they increased the chances of recording serious injuries in multivehicle crashes.

Conclusions

The older driver population has been associated with more severe crash injuries compared to other age groups due to their declining health. This study used five-year Alabama crash data from January 2014 to December 2018 to comprehensively evaluate the factors that are associated with various injuries sustained in crashes in which the older driver is deemed to be at-fault. The data set was split into single and multivehicle crashes, and a random parameter multinomial logit model with heterogeneity in mean and variance was employed to account for unobserved heterogeneity in the data. A wide range of factors affecting older drivers' injuries such as crash characteristics, land use characteristics, driver characteristics, roadway characteristics, vehicle characteristics etc. were considered. Marginal effects were estimated to measure and compare factors influencing older drivers' injury outcomes.

The modeling results show that, the variable "no air bag deployment" in single vehicle crashes reduces the likelihood of fatal and suspected serious injuries by 0.0072 and 0.016 respectively. In addition, male older drivers are more likely to be involved in fatal injuries whiles the probability of suspected serious and suspected minor injury is low. In terms of weather and lighting, driving in the rain and in the dark increases the likelihood of serious injuries in single-vehicle crashes. For multivehicle crashes, injuries are likely to be fatal when air bags are deployed during crashes. Other factors related to the manner of collision

Table 5
Comparison of marginal effects of significant variables common across the two crash types.

Crash variables	Single vehicle crash			Multivehicle crash		
	K	A	B	K	A	B
Clear weather	Low	High	Low	Low	High	Low
Retired	Low	Low	High	Low	High	High
Employed	Low	Low	High	Low	High	High
Driver age (65–75 years)	Low	High	Low	Low	High	High
Open country	High	Low	Low	High	Low	Low
Residential area	Low	Low	High	Low	High	High

in multivehicle crashes, such as angled collision, rear end, and sideswipe were also found to likely to result in suspected serious injury whiles side impacts and head-on collisions are likely to result in fatal and suspected serious injuries. Also, drivers between 65 and 75 years are likely to be involved in suspected serious injuries whiles the probability of fatal injuries is low for both single and multivehicle crashes. In addition, single and multivehicle crashes occurring at open countries are likely to be fatal since roads in the area are less congested and drivers usually drive at relatively higher speed.

Ultimately, this study made some interesting findings that may guide the implementation of crash countermeasures that target the safety concerns of the ageing population. For instance, the finding on the effect of airbag deployment on crash outcomes is particularly interesting and should be included in any safety campaigns and driver education. Efforts should also be made to support senior citizens to acquire newer vehicles that are equipped with advanced driver assist systems. These devices should address most of the major concerns associated with older drivers like running signals and stops at intersections, lane changes, blind spot warning and navigating complex intersections without necessarily distracting them. Also, on-demand public transportation can be made available, and the older population should be incentivized to use them to reduce the amount of driving they do. While many older drivers have already limited their travel activities to daytime, there is the need to provide enough information on the hazards of nighttime driving to encourage many more to avoid driving at night.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

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