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Factors associated with driver injury severity of motor vehicle crashes on sealed and unsealed pavements: Random parameter model with heterogeneity in means and variances

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ABSTRACT

The effect of sealed or unsealed road pavements on motorist's injury severities has not been extensively explored. This study collected a four-year crash dataset (2015–2018) from South Australia to explore this issue. The data shows 3,812 and 1,086 crashes at sealed and unsealed pavement surfaces, respectively, during those years. This study examines the consequence of sealed and unsealed pavements on driver injury severity outcomes of motor vehicle crashes. A mixed logit model was developed by accounting for heterogeneity in means and variances of the random parameters. The variables were distributed among several categories: driver, temporal, spatial, roadway characteristics, crash type, vehicle type, and vehicle movement. Four random parameters were observed in the sealed model, whereas five parameters were in the unsealed one. Moreover, the sealed pavements model showed substantial heterogeneity in means of four of the random parameters, while the unsealed pavements model has some heterogeneity in both means and variances of some of the random parameters. Marginal effect results indicate that two indicator variables have enlarged the likelihood of driver severe injury consequences in sealed, alcohol involvement and posted speed limit > 100 km/hr. Additionally, four other significant variables sustain the probability of severe injury outcomes at unsealed pavement like male drivers, middle-aged drivers, rollover crash types, and crashes at straight roads. Based on these variables, various countermeasures were recommended to enhance the safety of both types of pavements.

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Introduction

Road pavements play a significant role in traffic crashes due to the direct impact on both humans and vehicles (Lee et al., 2015). In particular, pavement state was found to have variable influences on crash frequencies and injury severities sustained by motor vehicle drivers (Buddhavarapu et al., 2013; Jiang et al., 2013; Anastasopoulos, 2016; Sarwar and Anastasopoulos, 2017; Afghari, Haque and Washington, 2020). Regarding pavement surface conditions, research shows that while dry pavement conditions have been identified as being positively associated with crash severity (Mehrara Molan and Ksaibati, 2020), slippery or wet pavement surface conditions have a negative impact as it mostly results in hydroplaning (Tamakloe et al., 2020). In general, excellent pavement condition (roads without potholes) has been related to lower accident rates (Li and Huang, 2014; Afghari et al., 2016). On the contrary, several studies concluded that excellent pavement surface conditions are associated with highly severe or fatal roadway crash outcomes, and poor pavement surface conditions may result in lower crash injury severities (Li et al., 2013; Lee et al., 2015; Alnawmasi and Mannering, 2019; Saeed et al., 2019; Hong et al., 2020). Since roadways with excellent and well-maintained pavement surfaces offer higher service levels, drivers are more likely to speed and be elaborate in risky driving performances.

Although numerous studies have investigated the influence of roadway pavement surface on crash severity outcomes, the literature that comprehensively explores and compares the effect of pavement surface type, namely sealed and unsealed pavements, is scarce and sparse. A sealed road is one whose surface has been permanently "sealed" or "paved" using surface treatments such as tar, bitumen, concrete, or asphalt (Alnedawiet al., 2019). The benefits of sealed roadways are abundant; nearly, they are known to improve the performance and level of service of roadways, improve upon the life of roadways (Sirivitmaitrie et al., 2011), and ensure low cost of road stabilization (Rivera et al., 2015). In contrast, "unsealed" or "unpaved" roads are not sealed with a hard material (Alnedawi and Rahman, 2021). Generally, most roadways are aimed to be sealed to provide smooth and comfortable rides to road users. However, in Australia, about 500,000 km (310685.6 miles) of public roads are unsealed, around 60% of the total road network (Van Wijk, 2020). The disproportional size of unsealed roadways is due to its geographical nature, as most of the population is concentrated in two widely separated coastal regions. This rare situation directly influences the road network structure connecting significant cities with regional towns. In addition, unsealed pavement is also most common in developing nations, usually covering over 80% of their roadway lengths and carries approximately 20% of their motorized traffic (Rivera et al., 2015).

Interestingly, concerning crash frequency, several studies identified that roadways with sealed surfaces negatively influence accident frequency (Afghari et al., 2016, Afghari et al., 2019). Regarding crash severity, Afghari et al. (2020) used a joint model of crash counts and crash severity to study crashes in Queensland, Australia. The study provided enough evidence to show that sealed pavements are related to decreased crash severity in the case study area. Similarly, Anowar et al. (2014) analyzed the influential factors of crashes in Bangladesh and found that sealed roadways had a negative impact on crash severity and unsealed pavement surfaces were related to increased crash severity. Shinstine et al. (2016) explored the factors affecting crash severities on rural roadways in Wyoming. The study identified that pavement surface type was a critical predictor of crash severity. Finally, regarding roadway shoulders surface types, Meuleners et al. (2011) observed that sealed roadway shoulders were highly effective at reducing the crash severity rates. The study recommended treating the unsealed shoulders to reduce vehicles' chance of moving out of the roadway or colliding with other vehicles when they make a sharp overcorrection after the vehicle comes into contact with unsealed shoulders.

It can be seen that the effect of sealed or unsealed road pavements on motorist's injuries-has not been extensively explored. It is unknown yet which of the explanatory factors might affect the injury severities under these two types of road pavements. Besides, the previous studies did not consider the heterogeneity in means and variances of the random parameters. Failure to consider heterogeneity in the means may lead to model specification error resulting in erroneous inferences (Hamed and Al-Eideh, 2020), and this may lead to the recommendation of inefficient traffic safety countermeasures (Ye and Lord, 2011).

The previous studies that analyzed the association between sealed and unsealed roadways and crash counts have employed approaches such as the negative binomial and its random parameters variant to interpretation for unobserved heterogeneity in crash data (Afghari et al., 2019) and a Bayesian latent class safety performance function (Afghari et al., 2016). Concerning injury severity, Anowar et al. (2014) employed the traditional ordered logit model, the generalized ordered logit model, and an in part obliged generalized ordered logit model to model crash severities due to the ordinal nature of the injury severity outcomes. Upon comparing the goodness-of-fit measures, the authors noted that the partially constrained generalized ordered logit model was more robust as it relaxes the parallel-lines assumption and is more parsimonious relative to the generalized ordered logit model (Williams, 2006). Several researchers have widely used random parameter or mixed models for dealing with unobserved heterogeneity (Anastasopoulos and Mannering, 2011; Yu and Abdel-Aty, 2014a; Han et al., 2018; Azimi et al., 2020; Wang et al., 2020; Yu et al., 2020). These models have the advantage of allowing parameters to contrast over perceptions to accommodate for individual unobserved heterogeneity. More robust methodologies that further accounts for heterogeneity in the means and variances of the random parameters have been explored (Ahmed et al., 2020; Behnood and Mannering, 2019, 2017a; Hamed and Al-Eideh, 2020; Huo et al., 2020; Yu et al., 2020). The demerit of this approach is that the modeler has to make distributional assumptions about how the parameters vary across observations (Cerwick et al., 2014). Therefore, this study has estimated an established mixed (random parameter) logit model (MXL) to recognize noteworthy contributing factors and assess their impact on the harm seriousness of drivers included in crashes at sealed and unsealed pavement conditions. The MXL model is a generalized methodological approach to address the existing limitations of the multinomial logit structure. It has been shown that the MXL model may be specified to approximate any discrete outcome model (Moore et al., 2011; Haleem and Gan, 2013; Wu et al., 2014; Behnood and Mannering, 2017a, 2017b; Seraneeprakarn et al., 2017; Zubaidi et al., 2021a).

This study investigates the impact of sealed and unsealed pavements on driver injury severity of motor vehicle crashes to address the research gaps. To achieve this goal, the crash dataset was clustered into two homogeneous groups (i.e., sealed and unsealed), and two mixed logit models were developed by accounting for heterogeneity in means and variances of the random parameters. The remaining of this study covers data description, methodology, results, discussion, and conclusions. Insightful findings were also identified to propose critical policy interventions.

Methodology.

Three distinct injury severity levels are measured in the current study: no injury or property damage only (PDO), minor injury (non-incapacitating injury), and severe injury (incapacitating or fatal injury). To begin constructing an MXL model, Eq. (1) is characterized as.

$$S_{kn} = \beta_k X_{kn} + \varepsilon_{kn} \tag{1}$$

where S_{kn} defines the severity function of crash n resulting in driver injury-severity level k ($k = 1, 2, 3$), β_k represents a vector of estimable parameters for driver injury-severity level k, X_{kn} denotes a vector of independent variables, and ε_{kn} is the error term is considered independent and identically distributed (Washington et al., 2011). This study also considers accounting for unobserved heterogeneity in the means and variances of the random parameters by letting βkn be a vector of estimable parameters that vary across these observations. Unobserved heterogeneity in the means and variances of random parameters as characterized in Eq. (2) is accounted by β_{kn}, and is defined as follows (Seraneeprakarn et al., 2017; Behnood and Mannering, 2019):

$$\beta_{kn} = \beta + \Theta_{kn} Z_{kn} + \sigma_{kn} EXP(\omega_{kn} W_{kn}) \upsilon_{kn} \tag{2}$$

where Θ_{kn} is a corresponding vector of estimable parameters, Z_{kn} is a vector of independent variables that gets the heterogeneity in the mean that influences specific driver injury-severity outcome k. W_{kn} is a vector of the explanatory variables that captures heterogeneity in the standard deviation σ_{kn} with comparing parameter vector ω_{kn}, and the disturbance term is (υ_{kn}).

When we allow the vector β_{kn} to assume a continuous density function such that $Prob\ (\beta_{kn} = \beta) = f(\beta|\varphi)$, and crash-specific unobserved heterogeneity is allowed, the likelihood of a driver in crash n incurring an injury severity of level k, $p_n(k)$, can be described formulated as follows (Behnood and Mannering, 2017a, 2017b; Seraneeprakarn et al., 2017):

$$p_n(k) = \int \frac{EXP\,(\beta_k X_{kn})}{\sum_{\forall I} EXP\,(\beta_k X_{kn})} f(\beta|\varphi) d\beta \tag{3}$$

where $p_n(k)$ is the likelihood of injury severity k in crash n where $f(\beta|\varphi)$ is the density function of β with φ referring to the vector of mean and variance parameters of that density function, and all remaining factors are characterized prior to that.

The model was estimated by utilizing simulated maximum likelihood with 1,000 Halton draws (McFadden and Train, 2000). Many different distributions for the random parameter were experimented. Overall, the normal distribution was identified to have the most excellent measurable fit in this study. To give more insight into the estimated results for assessing the impacts of various parameter estimates on the model outcomes, marginal effects were calculated. The marginal effect shows the impact of a one-unit increment in an indicator variable on the estimated probabilities (Washington et al., 2011; Tamakloe et al., 2022). For the continuous variable x_k case, the marginal effects are computed as follows.

$$ME = \frac{\partial P_n(k)}{\partial x_{nl}} = P_{kn}(\beta_{lk} - \bar{\beta}_n) \tag{4}$$

where $\bar{\beta}_n$ denotes the probability-weighted average of the coefficients in the model for different choice combinations, and β_{lk} is the slope coefficient contained in the coefficient vector β_k (Wulff, 2015). For values of x_{nl} the marginal effect estimate would be positive if $\beta_{lk} > \bar{\beta}_n$. Also, for some values of x_{nl}, then the estimate would be negative if $\beta_{lk} < \bar{\beta}_n$. For a dummy variable x_k, the discrete change in probabilities is computed as:

$$ME = \frac{\Delta P_n(k)}{\Delta x_{nl}} = P\left(k|\bar{x}, x_{nl} = 1\right) - P\left(k|\bar{x}, x_{nl} = 0\right) \tag{5}$$

Further information regarding the marginal effect estimation procedure is discussed by Wulff (2015). In an attempt to extend the current model thus far assumes that the random parameters are uncorrelated to a model in which the parameters are freely correlated, the diagonal elements are allowed to be nonzero.

Log-likelihood and transferability tests

This study conducted a sequence of likelihood ratio tests. The first log-likelihood ratio test for transferability is to measurably test the noteworthiness of utilizing a holistic model instead of separate models by road surface condition as follows:

$$\chi^2 = -2[LL_{Holistic} - LL_{Sealed} - LL_{Unsealed} \quad (6)$$

where $(LL_{Holistic})$ is the log-likelihood at the convergence of the model that utilized all of the accessible crash information regardless of pavement type, (LL_{Sealed}) is the log-likelihood at the convergence of the demonstrate based on information for sealed surface, $(LL_{Unsealed})$ is the log-likelihood at the convergence of a model based on data for the unsealed road surface.

To investigate the resemblance of parameter estimates between the different models, another transferability test was conducted. This test allows the users to subgroups of data stability of the estimated parameters as follows (Washington et al., 2011):

$$x^2 = -2\left[\left(\beta_{t1_{t2}}\right) - \left(\beta_{t1}\right)\right] \quad (7)$$

where $\left(\beta_{t1_{t2}}\right)$ is the log-likelihood at convergence for the converged parameters of the model t_1 using the data from models t_2 and (β_{t1}) is the log-likelihood at convergence for the converged parameters of the model t_1. For more clarification, $\left(\beta_{t1_{t2}}\right)$ refers to the model that utilizes sealed model with unsealed data and (β_{t1}) refers to the model that can predict this data.

Data description

The road crashes data in South Australia were used (Data.Sa, 2018), covering four years (2015–2018). Data was filtered to include motor-vehicle crashes at sealed and unsealed pavement surfaces with 3812 and 1086 crashes, respectively. The final dataset included detailed information about driver characteristics, crash type, vehicle type and movement, roadway characteristics, temporal and spatial characteristics. The provided injury severities were divided into no injury, minor injury, severe injury, and fatal injury. However, with the minimal number of observations of fatal injuries, that group was merged with severe injury to produce three groups: no injury, minor injury, and severe injury. Fig. 1 shows the distribution of the severity types on sealed and unsealed surfaces. Overall, a sealed surface has a more significant number of crashes-injury severities compared to an unsealed surface.

Table 1 demonstrates the descriptive statistics of all the significant variables for the two surface types after excluding all the insignificant variables, based on the coefficients, from the final models no matter the marginal effect's effect. The results indicated 26 variables were found significant in the sealed model, whereas 18 significant variables in the unsealed model.

Model estimation results

Loglikelihood and transferability tests results

The log-likelihood ratio test for testing the significance of utilizing the holistic model $(LL_{Holistic})$ over the separate models (LL_{Sealed}) and $(LL_{Unsealed})$, Eq. (6), came up with an associated critical chi-square value of 628.21 with 5 degrees of freedom that is break-even with the summation of the number of evaluated random parameters in separate models (sealed and unsealed models) minus the number of assessed random parameters in a holistic model. The results rejected the null hypothesis that

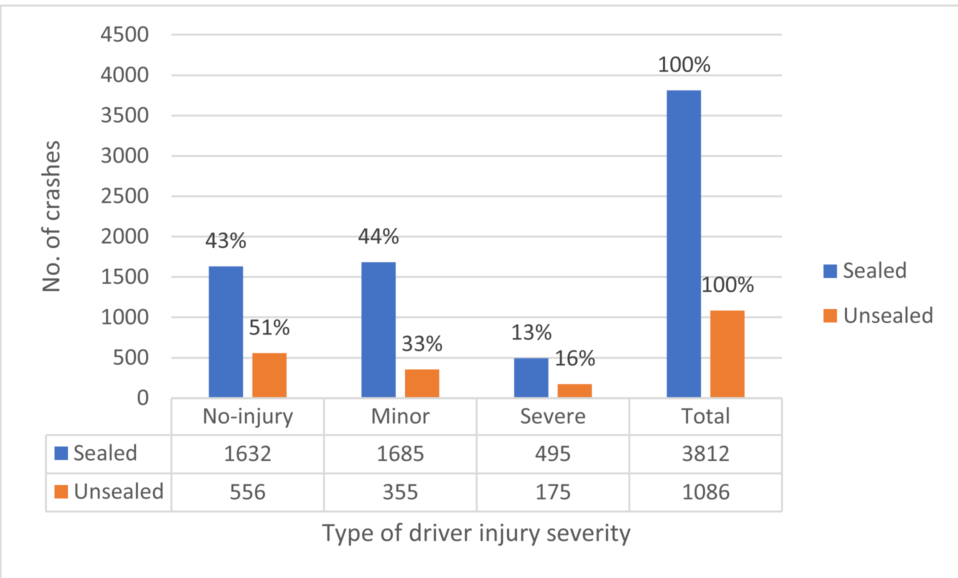

Fig. 1. Injury severity types for sealed and unsealed road surfaces.

Table 1
Descriptive statistics of the significant variables for sealed and unsealed models.

Variable	Sealed surface		Unsealed surface	
	Mean	S.D.	Mean	S.D.
Driver Characteristics				
Gender of driver (1 if female, 0 otherwise)	0.22	0.42		
Gender of driver (1 if male, 0 otherwise)	-	-	0.71	0.45
Driver age (1 if adult (21–35 yrs), 0 otherwise)	0.33	0.47	-	-
Driver age (1 if middle age (35–64 yrs.), 0 otherwise)	-	-	0.36	0.48
Driver license type (1 if full LIC, 0 otherwise)	-	-	0.61	0.49
Driver license type (1 if provisional LIC, 0 otherwise)	-	-	0.18	0.38
Driver license type (1 if learner LIC, 0 otherwise)	0.04	0.19	-	-
Alcohol indicator (1 if that participant had been drinking, 0 otherwise)	0.09	0.29	0.07	0.25
Safety equipment use (1 if seatbelt is not used, 0 otherwise)	0.98	0.15	0.98	0.15
Crash Type				
Number of vehicle occupants *(continuous)*	1.42	1.59	1.60	0.96
Crash type (1 if rollover crash, 0 otherwise)	0.76	0.43	0.86	0.35
Crash type (1 if hit ped cyclist, 0 otherwise)	0.11	0.31	-	-
Crash type (1 if heavy vehicle involved, 0 otherwise)	0.06	0.23	0.66	0.47
Vehicle Movement				
Vehicle movement (1 if turning left, 0 otherwise)	0.05	0.21	-	-
Vehicle movement (1 if swerving, 0 otherwise)	0.07	0.26	-	-
Vehicle movement (1 if entering driveway, 0 otherwise)	0.08	0.25	-	-
Vehicle Type				
Vehicle type (1 if passenger car, 0 otherwise)	0.51	0.50	0.78	0.41
Vehicle age (1 if vehicle age < 20 yrs., 0 otherwise)	0.63	0.48	-	-
Temporal Characteristics				
Time of the crash (if during nighttime between 12am-6am, 0 otherwise)	0.08	0.28	-	-
Time of the crash (if at morning between 6 am-12 pm, 0 otherwise)	0.26	0.44	-	-
Time of the crash (if at afternoon between 12 pm-6 pm, 0 otherwise)	0.33	0.47	0.39	0.49
Time of the crash (if during a daylight, 0 otherwise)	-	-	0.75	0.43
Weekends indicator (1 if the crash happened during the weekends, 0 otherwise)	0.35	0.48	-	-
Weekdays indicator (1 if the crash happened during the weekdays, 0 otherwise)	0.43	0.67	-	-
Season of the crash (1 if in Winter (June-August), 0 otherwise)	-	-	0.26	0.440
Spatial Characteristics				
Stats area (1 if the crash occurred within city, 0 otherwise)	0.03	0.15	-	-
Stats area (1 if the crash occurred within metropolitan, 0 otherwise)	0.48	0.50	-	-
Crash location (1 if at a work zone, 0 otherwise)			0.32	0.13
Roadway Characteristics				
Vertical alignment (1 if hill, 0 otherwise) [MI]	0.06	0.23	-	-
Roadway type (1 if freeway, 0 otherwise)	0.03	0.13	-	-
Posted speed limit (1 if the speed limit 50–100 km.hr, 0 otherwise)	0.53	0.50	0.21	0.41
Posted speed limit (1 if the speed limit more than 100 km/hr., 0 otherwise)	0.45	0.50	-	-
Pavement condition (1 if dry, 0 otherwise)	0.85	0.36	-	-
Pavement condition (1 if wet, 0 otherwise)	-	-	0.18	0.38
Horizontal alignment (1 if straight road, 0 otherwise)	-	-	0.53	0.50

Note: S.D. = standard deviation, (-) means the variable is insignificant in this model.

the holistic and separate models' parameters are equal with 99% confidence. The temporal instability has been tested by applying Eq. (7), $\beta_{t1_{t2}}$ refers to the sealed model using unsealed data and β_{t1} refers to the log-likelihood at convergence for the converged parameters of the sealed model. Results from this process for each model are shown in Table 2. The measurement with degrees of freedom equal to the number of assessed parameters can provide 99% confidence in the likelihood that the evaluated models have diverse parameters. So, the null hypothesis that the evaluated parameters are rising to between the two types of pavement can be excluded. Additionally, the correlated random parameter tests indicate that all the models with correlated parameters are not estimable. Therefore, the holistic model and all the models with correlated

Table 2
Transferability test outcomes (degrees of freedom numbers in the parentheses and confidence level in brackets).

t_1	t_2	
	Sealed (model)	Unsealed (model)
Sealed (Data)	0	164.34 (21) [>99.99 %]
Unsealed (Data)	186.26 (31) [>99.99 %]	0

parameters are eliminated from the result section, and the separate models with uncorrelated parameters have been presented and discussed thoroughly.

Driver characteristics

Many previous studies indicate a significant correlation between the driver characteristics and the occurrence of various crashes. In this study, driver gender plays a noteworthy part in the injury severity outcomes. As made known, the female driver indicator variable was significant by dropping the probability of no injuries by −0.040 in the sealed pavement (Table 3). On the other hand, the male driver indicator variable enlarged the possibility of severe injury by 0.078 for unsealed pavement models, as shown in Table 4 and Fig. 2. This could be explained as female drivers usually have less aggressive driving manners than male drivers.

Moreover, the male driver's parameter is random and normally distributed with a mean of 1.20 and a standard deviation of 1.96 in the severe injury-unsealed model. Based on this, about 27.02% of the gender of driver observations, males are related with lower severe injury prospect. In other words, 27.02% of the distribution is less than 0, and the remaining 72.98% is more than 0. This outcome is not in promise with previous studies (Kim et al., 2013; Weiss et al., 2014), and it is in line with (Chiou et al., 2013; Zubaidi et al., 2020).

Other variables related to different drivers' age have been found significant and sustain different types of injury severity probabilities. Adult drivers who are between 21 to 35 years were found to decline the prospect of minor and severe injury in the sealed model, as shown in Table 3. In comparison, middle-aged drivers were initiated to significantly raise the prospect of severe injury in unsealed models, as revealed in Table 4 and Fig. 3. It is expected that middle-aged drivers usually drive to remote areas for work, recreation, or other activities, while young drivers generally prefer to be in the city (using sealed roads).

Looking at the driver's license type, drivers with learner license results in Table 3 show a diminish within the likelihood of no injury by −0.021 in the sealed model, and the indicator variable was not substantial in the unsealed model. This could be attributed to the learner drivers' lack of experience, weak driving skills, risk-related behavior, and poor judgment about expected driving circumstances. On the other hand, the drivers with provisional and full licenses were significant and enlarged the possibility of no injury by 0.019 and 0.014, respectively, in the unsealed model, as shown in Table 4. These results depict that the drivers with provisional and full have more experience compared to the learner drivers. Generally, driver experience is one of the humanitarian factors that help avoid accidents, given the skills individuals have acquired due to their long dealing with their cars, other drivers, and roads.

Furthermore, drivers under alcohol effects significantly increased the likelihood of minor injury by 0.048 and severe injury by 0.075 in the sealed model, as shown in Fig. 4. A similar effect was observed in the unsealed model. Driving under the impact of alcohol is one of the leading causes of vehicle crashes. This adversely affects the driver by decreasing the perception reaction, vehicle control, and driver alertness, which are essential aspects of the driving process. These observations are similar to previous studies that identified that the most severe reported injuries were due to alcohol's influence (Behnood et al., 2014; Zubaidi et al., 2021b).

Another significant driver characteristic that was found to impact driver seriousness is utilizing the seatbelt. Table 3 and Table 4 show that the seatbelt parameter was random and normally distributed, influencing injury severity outcomes. The random parameter had means of −0.85 (-2.93) and standard deviations of 5.88 (1.48) in sealed (unsealed) models. The result showed that a proportion of some observed an accident that occurs while driving on a sealed and unsealed pavement without using the seatbelt are additional prospective to reason a severe injury for the drivers. This result might be due to the fact that, generally, utilizing a safety belt is considered one of the essential safety equipment tolls that reduce the percentage of fatal injuries in traffic accidents. The defensive impact of seatbelts has been confirmed and assessed in plentiful studies (Eluru and Bhat, 2007; Chen et al., 2016).

Crash type

Numerous studies have been conducted on the crash types under different conditions and related these crashes to specific driver injury severity. In the current study, many different crash categories have been found to have a different correlation with different injury severity outcomes. One of these factors is the number of vehicle occupants, which was found to decline the driver's probability of getting no injury and raise minor injury prospects in both models. This might be because interference from passengers and many improper occupants' behaviors may lead to driving distraction, causing more severe crashes.

Moreover, a vehicle with turning right movement was found to increase the prospect of no injury by 0.016 in the sealed model, and this might be because drivers tend to decrease speed during making any turns, which make the crashes less severe. Hitting pedestrians and cyclists was found to raise the likelihood of minor injury in the sealed model only. Generally, it is not expected to see a cyclist on the unsealed pavement, making this variable insignificant in the unsealed pavement.

Another crucial crash category is the rollover crash, found to raise the likelihood of severe injury in both sealed and unsealed pavement is rollover crash (see Fig. 5). In this study, the estimated results indicate that this indicator variable has a random parameter normally distributed in both models. Tables 3 and 4 show that the random parameter of rollover crash had −2.39 and 1.19 and standard deviations of 2.18 and 1.23 for sealed and unsealed models. This suggests that about 86% of rollovers crashes have a lower possibility of being elaborate in severe injury conclusions, while 14% of them have an

Table 3
Mixed logit model with heterogeneity in mean results for sealed pavement.

Variable	Coefficient	t-stat	Marginal effect		
			No-injury	Minor	Severe
Constant [MI*]	−1.02	−7.60	-	-	-
Constant [SI**]	−1.00	−5.58	-	-	-
Driver Characteristics					
Gender of driver (1 if female, 0 otherwise) [NI*]	−0.32	−3.55	**−0.040**	0.032	0.008
Driver age (1 if adult (21–35 yrs), 0 otherwise) [MI]	−0.24	−3.05	0.036	**−0.044**	0.008
Driver age (1 if adult (21–35 yrs), 0 otherwise) [SI]	−1.66	−1.69	0.016	0.018	**−0.34**
Driver license type (1 if learner LIC, 0 otherwise) [NI]	−0.83	−4.34	**−0.021**	0.011	0.010
Alcohol indicator (1 if that participant had been drinking, 0 otherwise) [MI]	0.83	5.89	−0.048	**0.058**	−0.010
Alcohol indicator (1 if that participant had been drinking, 0 otherwise) [SI]	1.58	3.60	−0.035	−0.040	**0.075**
Safety equipment use (1 if seatbelt is not used, 0 otherwise) [SI]	−0.85	−1.43	0.007	0.017	**−0.024**
Standard Deviation of Parameter, Normally Distributed	5.88	2.87	-	-	-
Crash Type					
Number of vehicle occupants [NI]	−0.04	−1.78	**−0.031**	0.019	0.012
Vehicle movement (1 if turning right, 0 otherwise) [NI]	0.14	2.91	**0.016**	−0.009	−0.007
Crash type (1 if hit ped cyclist, 0 otherwise) [MI]	2.21	2.69	−0.013	**0.025**	−0.012
Crash type (1 if Rollover crash, 0 otherwise) [SI]	−2.39	−5.25	−0.016	−0.027	**0.043**
Standard Deviation of Parameter, Normally Distributed	2.18	2.20	-	-	-
Crash type (1 if heavy vehicle involved, 0 otherwise) [SI]	−3.77	−3.64	0.045	0.053	**−0.098**
Vehicle Movement					
Vehicle movement (1 if turning left, 0 otherwise) [SI]	−0.97	−1.91	0.026	0.022	**−0.048**
Vehicle movement (1 if swerving, 0 otherwise) [SI]	−1.45	−3.30	0.016	0.013	**−0.029**
Vehicle movement (1 if entering driveway, 0 otherwise) [SI]	−0.40	−1.96	0.006	0.011	**−0.017**
Vehicle Type					
Vehicle type (1 if passenger car, 0 otherwise) [SI]	−1.78	−3.88	0.014	0.043	**−0.057**
Vehicle age (1 if vehicle age < 20 yrs., 0 otherwise) [SI]	−3.60	−3.22	0.016	0.034	**−0.050**
Standard Deviation of Parameter, Normally Distributed	3.41	3.22	-	-	-
Temporal Characteristics					
Time of the crash (if during nighttime between 12am-6am, 0 otherwise) [NI]	0.29	1.96	**0.019**	−0.014	−0.005
Time of the crash (if at morning between 6 am-12 pm, 0 otherwise) [MI]	0.26	2.60	−0.027	**0.039**	−0.012
Time of the crash (if at afternoon between 12 pm-6 pm, 0 otherwise) [NI]	−0.25	−2.77	**−0.045**	0.028	0.071
Weekends indicator (1 if the crash happened during the weekends, 0 otherwise) [NI]	−1.413	−2.04	**−0.075**	0.057	0.018
Weekdays indicator (1 if the crash happened during the weekdays, 0 otherwise) [MI]	−7.44	−2.05	0.031	**−0.059**	0.028
Spatial Characteristics					
Stats area (1 if the crash occurred within city, 0 otherwise) [NI]	−0.75	−2.57	**−0.012**	0.004	0.008
Stats area (1 if the crash occurred within metropolitan, 0 otherwise) [NI]	−1.82	−3.79	**−0.005**	0.003	0.002
Stats area (1 if the crash occurred within metropolitan, 0 otherwise) [MI]	2.77	3.79	−0.011	**0.008**	0.003
Roadway Characteristics					
Roadway type (1 if divided road, 0 otherwise) [MI]	0.16	2.24	−0.007	**0.009**	−0.002
Vertical alignment (1 if hill, 0 otherwise) [MI]	0.37	2.37	−0.012	**0.019**	−0.007
Roadway type (1 if freeway, 0 otherwise) [NI]	0.58	1.96	**0.013**	−0.007	−0.006
Posted speed limit (1 if the speed limit 50–100 km.hr, 0 otherwise) [NI]	−0.19	−1.81	**−0.058**	0.045	0.013
Posted speed limit (1 if the speed limit more than 100 km/hr., 0 otherwise) [SI]	4.00	2.80	−0.009	−0.015	**0.024**
Standard Deviation of Parameter, Normally Distributed	2.43	1.99	-	-	-
Surface condition (1 if dry, 0 otherwise) [NI]	−0.54	−5.13	**−0.035**	0.014	0.021
Heterogeneity in the mean					
Speed limit > 100 km.h[SI]: Stats area (1 if the crash occurred within metropolitan, 0 otherwise)	−1.14	−2.48	-	-	-
Rollover type crash [SI]: Time of the crash (if during nighttime between 12am-6am, 0 otherwise)	1.28	1.83	-	-	-
Modern vehicle [SI]: Stats area (1 if the crash occurred within metropolitan, 0 otherwise)	−0.84	−3.86	-	-	-
Not using the seatbelt [SI]: Stats area (1 if the crash occurred within metropolitan, 0 otherwise)	−1.23	−3.89	-	-	-
Not using the seatbelt [SI]: Time of the crash (if during nighttime between 12am-6am, 0 otherwise)	−0.71	−2.59	-	-	-
Model Statistics					
Log-likelihood at convergence	−3455.86				
Log-likelihood at constant	−5184.61				
McFadden Pseudo R-squared	0.33				
AIC	3945.7				
No. of observations	3812				

[*] MI = Minor Injury, [**]SI = Severe Injury, [***]NI = No Injury.

extra possibility in the sealed model, while the unsealed model indicated that 16.67 % have a mean less than zero and about 83.33% have a mean more than zero.

Rollover accidents occur due to different causes like driving under the impact of alcohol, losing control of the vehicle, overspeeding, fatigue and exhaustion, and reduced vision in specific conditions Bhowmik et al., 2021. Finally, looking to

Table 4
Mixed logit model with heterogeneity in mean and variance results for unsealed pavement.

Variable	Coeff	t-stat	Marginal effect No-injury	Minor	Severe
Constant [MI]	−2.72	−2.63	-	-	-
Constant [SI]	1.98	3.13	-	-	-
Driver Characteristics					
Gender of driver (1 if male, 0 otherwise) [SI]	1.20	1.97	−0.024	−0.054	**0.078**
Standard Deviation of Parameter, Normally Distributed	1.96	4.56			
Driver age (1 if middle age (35–64 yrs), 0 otherwise) [SI]	1.22	2.18	−0.024	−0.046	**0.071**
Driver license type (1 if provisional LIC, 0 otherwise) [NI]	0.13	2.52	**0.019**	−0.011	−0.008
Driver license type (1 if full LIC, 0 otherwise) [NI]	0.58	2.88	**0.014**	−0.008	−0.006
Alcohol indicator (1 if that participant had been drinking, 0 otherwise) [NI]	−1.83	−4.90	**−0.023**	0.015	0.008
Safety equipment use (1 if seatbelt is not used, 0 otherwise) [SI]	−2.93	−3.02	0.011	0.013	**−0.024**
Standard Deviation of Parameter, Normally Distributed	1.48	2.01	-	-	-
Crash Type					
Number of vehicle occupant *(continues)* [MI]	0.18	2.27	−0.031	**0.067**	−0.036
Crash type (1 if rollover crash, 0 otherwise) [MI]	0.65	2.95	−0.004	**0.016**	−0.012
Crash type (1 if rollover crash, 0 otherwise) [SI]	1.19	2.33	−0.027	−0.035	**0.062**
Standard Deviation of Parameter, Normally Distributed	1.23	2.35			
Crash type (1 if heavy truck involved, 0 otherwise) [SI]	−3.43	−4.11	0.012	0.011	**−0.023**
Standard Deviation of Parameter, Normally Distributed	3.76	5.56			
Crash location (1 if at a work zone, 0 otherwise) [MI]	1.36	1.99	−0.011	**0.017**	0.006
Vehicle Type					
Vehicle type (1 if passenger car, 0 otherwise) [MI]	−1.61	−7.51	0.012	**−0.033**	0.021
Temporal Characteristics					
Time of the crash (if during afternoon between 12 pm-6 pm, 0 otherwise) [SI]	−0.08	−2.57	0.006	0.017	**−0.023**
Time of the crash (if during a daylight, 0 otherwise) [NI]	−0.19	−2.01	**−0.061**	0.030	0.031
Season of the crash (1 if in Winter (June-August), 0 otherwise) [NI]	−0.19	−2.05	**−0.029**	0.017	0.012
Roadway Characteristics					
Posted speed limit (1 if the speed limit 50–100 km/hr., 0 otherwise) [SI]	−1.56	−1.88	0.010	0.021	**−0.031**
Surface condition (1 if wet, 0 otherwise) [NI]	0.38	1.77	**0.011**	−0.005	−0.006
Horizontal alignment (1 if straight road, 0 otherwise) [SI]	1.25	1.73	−0.017	−0.012	**0.029**
Standard Deviation of Parameter, Normally Distributed	4.07	4.58	-	-	-
Heterogeneity in mean					
Male driver [SI]: Number of vehicle occupants	−4.67	−2.27	-	-	-
Heavy truck involvement [SI]: Driver license type (1 if full, 0 otherwise)	1.05	1.80	-	-	-
Horizontal straight road [SI]: Number of vehicle occupants	−1.15	−2.42	-	-	-
Horizontal straight road [SI]: Time of the crash (if at afternoon between 12 pm-6 pm, 0 otherwise)	2.26	1.83	-	-	-
Rollover crash [SI]: Driver license type (1 if full LIC, 0 otherwise)	0.53	2.48	-	-	-
Not using a seatbelt [SI]: Driver license type (1 if full, 0 otherwise)	−1.47	−2.45	-	-	-
Heterogeneity in variance					
Horizontal straight road [SI]: Number of vehicle occupants *(continues)*	−1.59	−3.05	-	-	-
Not using a seatbelt [SI]: Number of vehicle occupants *(continues)*	−0.88	−4.79	-	-	-
Model statistics					
Log-likelihood at convergence	−946.59				
Log-likelihood at constant	−1388.63				
McFadden Pseudo R-squared	0.32				
AIC	1109.2				
Estimation based on N	1086				

crash type (1 if the heavy vehicle involved, 0 otherwise), the indicator variable has declined the prospect of severe injury and increased the prospect of no and minor injuries in both models. However, the indicator variable was found to have a random and normally distributed estimated parameter in the unsealed model with a mean of −3.43 and a standard deviation of 3.76. This outcome supports the proposition that drivers in those crashes are more likely to get severe wounds than have no severe injury.

Vehicle movement

Regarding the vehicle movement indicator variable, many different vehicle movements were significant and sustained less probability of severe injury. In the current study, turning left, swerving, and entering the driveway reduced the possibility of severe injury by –0.048, −0.029, and −0.017, respectively, and increased the possibility of no minor injuries in the sealed model. This could be plausible as drivers tend to reduce speed and concentrate while making any maneuvers.

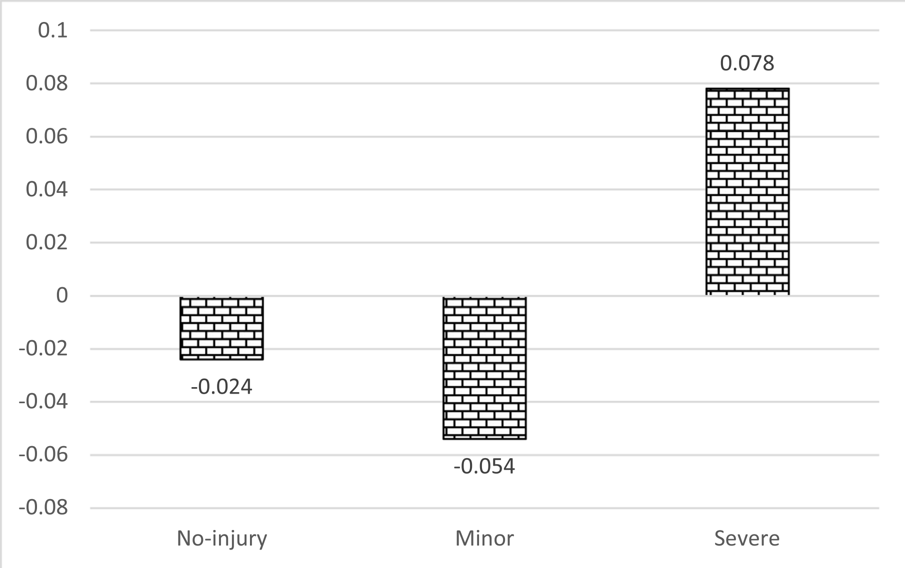

Fig. 2. Marginal effect of the indicator variable of the male driver at unsealed pavement.

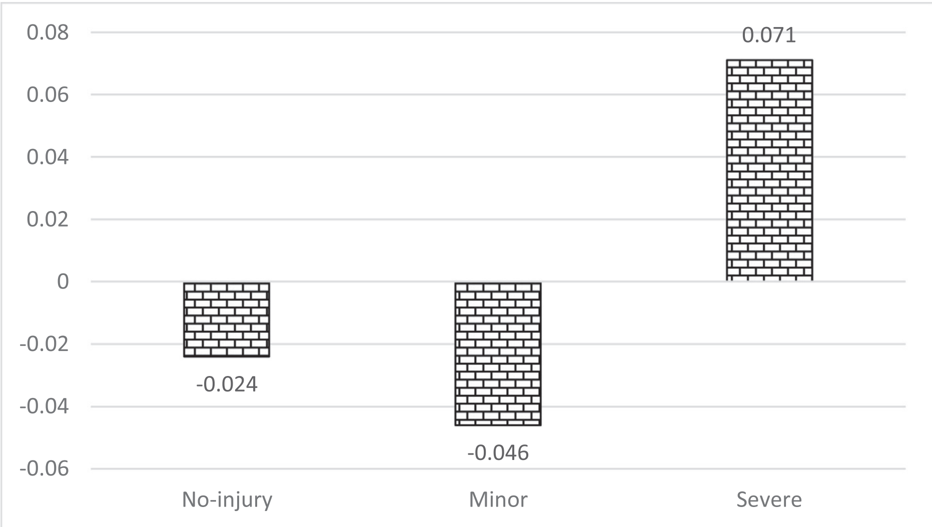

Fig. 3. Marginal effect of the indicator variable of the middle-aged driver at unsealed pavement.

Vehicle type

Another significant variable is the vehicle type; the results indicate that the passenger car plays different roles with the injury severity consequences. The passenger car indicator was found to diminution the prospect of severe injury through −0.057 sealed model besides raising the prospect of no, in addition, minor injuries by 0.014 and 0.043 in the sealed model. In comparison, the same variable was found to decline the possibility of minor injury by −0.033 in the unsealed model. Another crucial indicator factor related to vehicle type is the effect of vehicle age. If less than 20 years, the vehicle age indicator variable was significant, as shown in Table 3, and found to be random (with a normal distribution). The distribution parameters are estimated to have a mean of −0.360 and a standard deviation of 3.41 for severe injury, which specifies that around 54.2% of this normal distribution is lower than zero, and −45.8 % of the distribution is above zero. This infers that the possibility of severe injury rises by 45.8%, while for the majority (54.2%) of crashes, this probability tends to diminish.

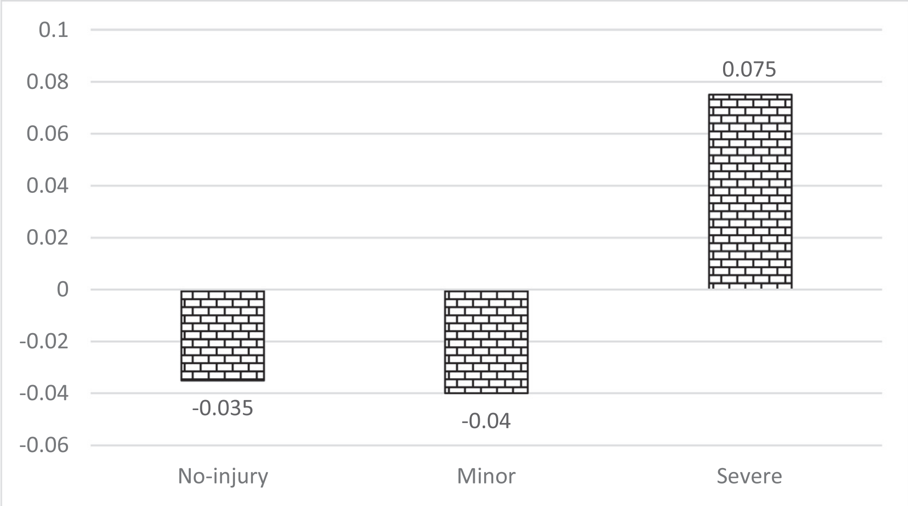

Fig. 4. Marginal effect of the indicator variable of the alchocol involvemnt at sealed pavement.

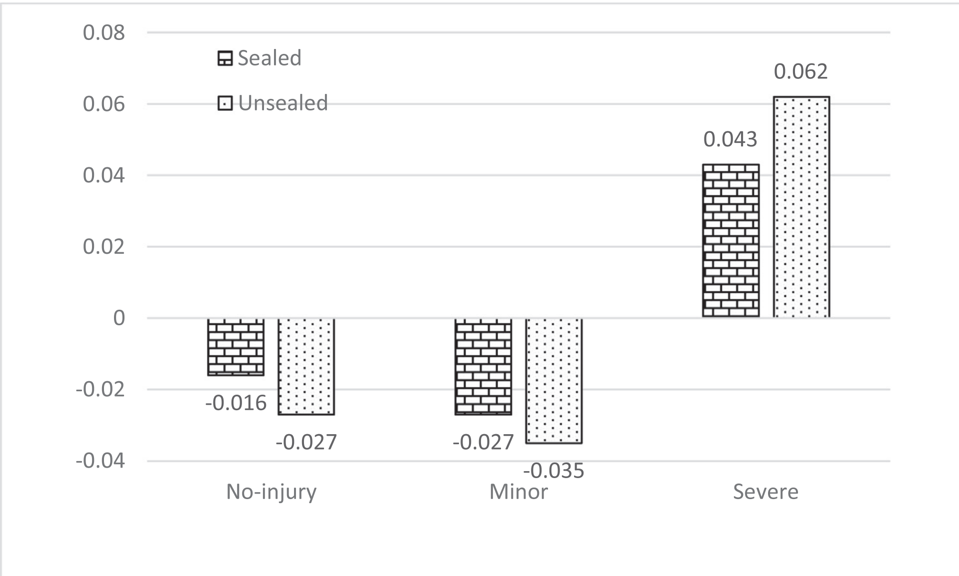

Fig. 5. Marginal effect of the indicator variable of the rollover crash type at sealed and unsealed pavement.

Temporal characteristics

In the current study, nighttime, morning, and afternoon were found significant in the different models. Table 3 shows that crashes during nighttime between 12 am-6 am are associated with a growth in the option of no injury by 0.019 and a reduction in minor and severe injuries by −0.014 and −0.005, correspondingly in the sealed model only. It might be related to low traffic volume at nighttime (Preusser et al., 1993; Foss et al., 2001; Ma et al., 2016). Furthermore, crashes in the morning between 6 am-12 pm were found to raise the prospect of minor injury in the sealed model only, as shown in Table 3. This supports Yu and Abdel-Aty's (2014b) findings that severe crashes are further expected to occur through the daytime. Crashes in the afternoon between 12 pm-6 pm were found to decline the prospect of no injury and raise the probability of minor and severe injuries in the sealed model. However, this indicator variable was found to decrease the probability of severe injury also raise the probability of no and minor injuries in the unsealed model, as shown in Table 4. The afternoon timing's negative impact on the driver injury severities at the sealed roads could be related to rush hours; rare to have such activities in the rural areas (unsealed pavement).

Concerning the time of day when vehicle crashes occurred during daylight, the probability of no injury decreased by −0.061in the unsealed model, as shown in Table 4. This might be because drivers generally feel more comfortable driving during the daylight, leading to less awareness and higher speed as circumstances fewer injury outcomes. Moving to crashes that happened during the weekends, the indicator variable was associated with a decreased possibility of no injury and increased the possibility of minor and severe injuries in the sealed model. It might be related to the many trips during weekends, and some of them might be for long-distance. This result aligns with previously published research (Quddus et al., 2010; Ko et al., 2018).

Moreover, crashes during the weekdays were found to diminution the prospect of minor injury by −0.059 in the sealed model. Weekday crashes have been extensively considered in prior investigate (K et al., 2003; Yu and Abdel-Aty, 2013). Lastly, the crash season (1 if in winter (June-August), 0 otherwise) is associated with a reduction in the probability of no injury by −0.029 and growth in minor and severe injuries in the unsealed model as shown in Table 4. This might be related to the adverse weather condition during these months that could affect the driver perception reaction time, especially under snow and rain weather that play a significant role on the pavement friction level.

Spatial characteristics

Moving to demographic characteristics, the result indicates that crashes that occurred within the city were found to be significant and decrease the likelihood of no injury by −0.012 and increase the minor and severe injuries by 0.004 and 0.008, respectively, in the sealed model only. Furthermore, if the crash occurred within the metropolitan area, there will be a decrease in the probability of no injury by −0.005 and an increase in the minor injury by 0.008 in the sealed model (Table 3). Several studies were attentive to the consequence of state area on crash injury severity (Zubaidi et al., 2021b).

Finally, crash location (1 if at a work zone, 0 otherwise) was significant and increased the likelihood of minor and severe injuries in the sealed model and increased the likelihood of no injury outcome in the unsealed model only (Table 4). Drivers cruising on rural roads tend to drive faster due to the low traffic volumes, making motorists take a longer time to respond to the change in the work zones' traffic conditions.

Roadway characteristics

Road type (1 if divided road, 0 otherwise) was more probable to affect minor injury outcome and less possible to be no injury and severe injuries in the sealed model, as shown in Table 3. Vertical alignment (1 if hill, 0 otherwise) has similar outcomes to the previous indicator variable and in the sealed model only. As shown, roadway type (1 if freeway, 0 otherwise) regularly leads to less severe injuries (positive marginal effects for no injury and negative marginal effects for a minor injury and severe injury) in the sealed model. This finding could be related to smooth traffic flow with minimum conflict points. Posted speed limit (1 if the speed limit 50–100 km/hr., 0 otherwise) was found to be a fixed parameter that significantly reduced the likelihood of no injury accidents for the sealed model (Table 3), while the indicator variable significantly reduced the likelihood of severe injury accidents for the unsealed model (Table 4). A probable clarification is that motorists are usually more thoughtful while driving on low-level service roads such as unsealed pavements. Several earlier studies investigated the impacts of speed limits more than 50 km/hr on crashes severity (Zhu and Srinivasan, 2011; Cerwick et al., 2014).

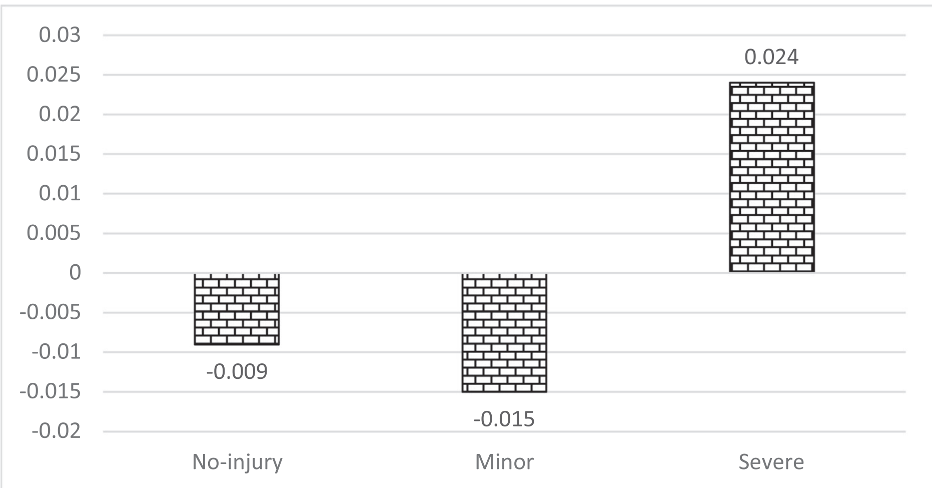

Fig. 6. Marginal effect of the indicator variable of the posted sped limit > 100 km/hr at sealed pavement.

The posted speed limit of more than 100 km/hr. was found to be a normally distributed parameter with a mean of 4 and a standard deviation of 2.43 in the sealed model only. Based on this, 5% of the crashes with a speed limit of more than 100 km/hr were associated with less severe injury probability. This variable sustained severe probability with 0.024, as shown in Fig. 6.

Moving to the dry surface, the indicator variable declines the possibility of no injury and raises the likelihood of minor and severe injuries in the sealed model, while the opposite trend was found in the unsealed model. It might be associated with high speed for sealed roads, and drivers tend to drive faster than usual on roads with good pavement conditions (Mannering, 2009). Dust on the unsealed pavements can be considered an influential factor in unsealed roadway crashes. Using a dust retarder and continuing standard maintenance of unsealed roadways can improve safety on unsealed roadways. The straight road alignment results with a mean of 1,25 and standard deviation of 4.07 indicated that crashes that happened within these roads were related to more severe injuries shown in Fig. 7.

Heterogeneity in mean and variance measures of the random parameters

All explanatory variables in sealed and unsealed models were tested for possible heterogeneity in the mean and variance measures of random parameters. The sealed pavements model showed substantial heterogeneity in means of four random parameters, as shown in Table 3, while the unsealed pavements model has some heterogeneity in both means and variances of some random parameters (Table 4).

In the sealed model (Table 3), crashes within the metropolitan area were found to expressively decreases the mean of the random parameter speed limit > 100 km/h. This suggests less severe injury severity when speeding more than 100 km/h in metropolitan areas and could be likely due to the improved road infrastructure. The same indicator variable (Stats area within metropolitan) also decreases the severe crash injuries of the random parameters modern vehicles and not using a seat belt. In addition, crashes during nighttime between 12 am-6 am, decrease the mean of the parameter not using the seatbelt. The same variable, nighttime crashes, raises the mean of the random parameter rollover crashes. This means more severe injuries from rollover crashes at nighttime are expected. This finding is intuitive as drivers cruising on sealed pavements are likely to overspeed and drive carelessly during the midnight hours when traffic volume is low.

The result of the mixed logit model of the unsealed pavement (Table 4) listed four variables affecting the mean of some of the random parameters and one variable affecting the variance of two random parameters. The number of vehicle occupants decreases the mean of both male drivers and horizontal straight roads. In particular, it has been established that men are likely to drive aggressively and indulge in risky driving behaviors. Besides, drivers are also less cautious when they cruize on straight roads with no curves (Tamakloe, Hong and Park, 2020). These behaviors lead to severe ramifications in the event of a crash. However, based on the findings, it could be inferred that when the number of vehicle occupants increases, male drivers would be more careful, and those negotiating curves on straight roads would be extra cautious due to possible complaints from the other people in the vehicle – thus, reducing the severity of injuries sustained in the crash when it occurs. The study also identified that a full driving license increases the mean of a rollover crash and reductions the mean of not using a seatbelt. Again, this outcome is probable as there is a high tendency of full license holders to feel confident as they believe they can handle dangerous situations appropriately. This increases their involvement in even greater forms of risky driving, increasing the severity of crashes (Lam, 2003). Time of the crash (if at afternoon between 12 pm – 6 pm, 0 other-

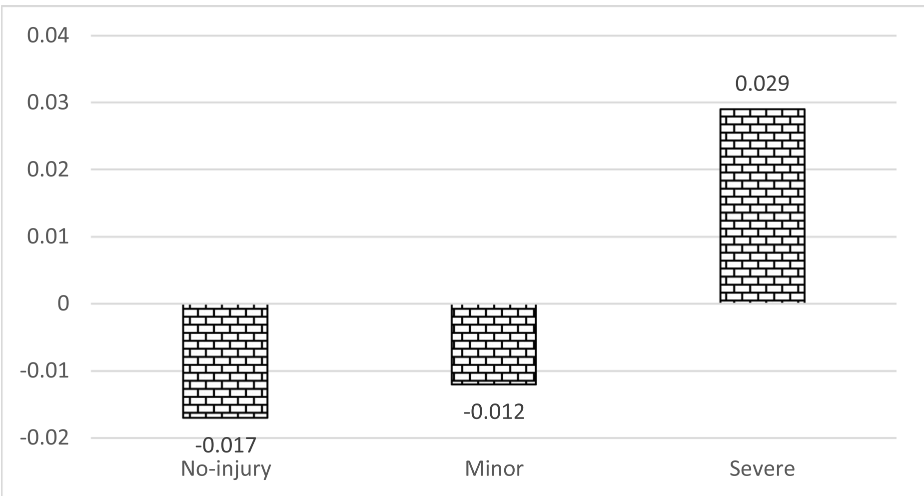

Fig. 7. Marginal effect of the indicator variable of the straight roads at unsealed pavement.

wise) increases the mean of horizontal straight road, which indicates that more severe injuries in afternoon crashes are expected while driving at horizontal unsealed roads. This finding is plausible as drivers are likely to drive fast or tired during that period when the roads are less congested. Finally, only the number of vehicle occupants (continues) decreased the variances of the horizontal straight road's random parameters and not using a seatbelt. The decrease in these two indicator variables' variances makes their distribution narrower and decreases their randomness and vice versa.

Conclusion and recommendations

This study investigated the impact of sealed and unsealed pavements on driver injury severity of motor vehicle crashes. Crash data from South Australia were used, covering four years (2015–2018). Mixed logit modeling with heterogeneity in means and variances of the random parameters was used to account for the unobserved heterogeneity problem characteristic of crash data.

The study identified various significant variables that affect the severity of injuries sustained by motorists driving on both sealed and unsealed road pavements. Rollover crashes were found to increase the chance of observing severe crashes on both sealed and unsealed roads. On the other hand, crashes with heavy vehicles and using seat belts are likely to reduce the chance of severe crashes on both sealed and unsealed roads. Essentially, we identified that some variables were not significant in both models when the seity function is defined for specific severity outcomes. For example, defined for severe injury category, while alcohol-impaired driving and driving on high-speed roads increased the chance for severe crashes on sealed roads, driving in the afternoon resulted otherwise. These variables were not significant under the unsealed road case when the injury severity function is defined for the severe injury category. On unsealed roads, males, middle-aged drivers, and those driving on straight roads have a higher chance of being involved in severe injury crashes. Defined for the severe injury category, these were not significant in the sealed road case. Interestingly, all the random parameters identified in both models significantly impacted the severity outcomes of crashes. In addition, two random parameters, namely seat belt and rollover crash, were shared between sealed and unsealed models. It was also identified that the sealed pavements model showed significant heterogeneity in means of four of the random parameters, while the unsealed pavements model has some heterogeneity in both means and variances of some of the random parameters. A comparison have been created in Appendix (1) shows the improvements on some performance measures of the unsealed pavement model with heterogeneity in mean and with the same model with heterogeneity in both of mean and variance. Marginal effect results indicate that two indicator variables increase the prospect of driver injury severities when the crash occurs on sealed roads. These indicators are alcohol involvement and posted speed limit > 100 km/hr. Additionally, four other significant variables were found to increase the probability of severe injury outcomes on the unsealed pavement. These indicators are male drivers, middle-aged drivers, rollover crash types, and crashes at straight roads.

Based on the study's findings, the following key conclusions were obtained, and relevant engineering, enforcement and educational countermeasures were provided to help address the issues identified.

- The finding that rollover crashes are likely to result in severe injuries when they occur on both sealed and unsealed roads could be indicative of the fact that drivers are less likely to engage in speeding behaviors and are less careful when negotiating tight curves. Interestingly, the study identified that injury severity was likely to increase further when the crash occurred at night between 12 am to 6 am (sealed road case) and when the driver had a full license (unsealed road case). This finding is plausible as drivers are less likely to adjust their speeds to the night conditions when traffic volume is low and when road conditions are good (sealed road case). Thus, rollover crashes occurring at such times may be due to overspeeding or reckless driving. While putting measures in place to monitor and control speeding and dangerous driving at night could help reduce these crashes, it is imperative to provide speed limit signs, improve curves safety by using curve warning signs and install appropriate crash barriers. In the long term, it would be worthwhile to identify critical hotspots for rollover crashes and to classify them for roadway geometry improvement to enhance sight distance. Interestingly, full license holders were found to increase the probability of severe injuries in rollover crashes, which could be due to their overconfidence (Lam, 2003) or the failure to undergo the proper training before acquiring a genuine license (Tamakloe et al., 2022). Again, while driver education and retraining are necessary, there is a need for further studies to understand the reason behind this occurrence.
- Driving while under the influence of alcohol on sealed roads was found to result in severe injury crashes. This finding is intuitive as alcohol has been identified to impair the judgement of road users and lead them into making wrong decisions. On sealed roads where traffic speeds are usually high, driving under the influence of alcohol could result in fatal crashes. To address this issue, it is imperative to lower the upper limit of the Blood Alcohol Concentration (BAC) in Australia and increase the sobriety check and random breath-testing points in the country. This would help deter drivers from drinking and driving. This problem could also be addressed by rolling out safety campaigns and educating drivers on the dangers of drinking and driving.
- Middle-aged drivers were more likely to be involved in severe injuries when they drive on unsealed roads, which is likely because they tend to drive to remote areas for work, recreation, or other activities (across unsealed roads), while young drivers generally preferred to be in the city (using sealed roads). As these roads are likely to lack proper lighting facilities, safety accommodations, and legible road signs, which are supposed to aid these older drivers to drive safely, it is likely

that they will be involved in crashes (Tamakloe et al., 2021). This finding calls for the need to intensify driver education on the need to drive safely on unsealed roads and provide adequate funds for designing such roads and providing visible road signs to help middle-aged drivers drive safely.
- Motorists on sealed roads with high-speed limits were identified to have a high propensity for serious injury crashes, while those on unsealed roads are likely to result in minor or no injuries. In addition, crashes on straight roads were likely to result in severe consequences, particularly on unsealed roads. These findings are intuitive as drivers are likely to engage in risky driving behaviors when they perceive the roadway conditions as good. To address the issue of speeding, it would be worthwhile to provide clearly visible speed limits on roadways and to use optical speed bars on the pavement to create an illusion to reduce the speed. Finally, we recommend tightening speed limit regulations in terms of increasing enforcement in terms of using speed cameras to identify and punish drivers who overspeed. Regarding the issue of serious crashes on straight roads, we recommend the increase of enforcement such as police presence to check risky behaviors on straight road sections.
- The finding that driving during the period between 12 pm to 6 pm positively impacts the driver injury severities when the driver is involved in a crash on sealed roads could be due to fatigue, speeding behaviors and high interaction between vehicles during that period. As drivers cruising on sealed roads perceive the road conditions as good, it is likely that they will be less careful. While educating drivers on the need to rest could help address this issue, it is also crucial to increase traffic monitoring activities during the afternoon and evening periods to ensure that drivers conform to traffic regulations.

This study contributes to the literature on traffic safety by providing a deeper understanding of the factors influencing injury severities sustained in crashes on both sealed and unsealed roads in the country. Although the issues regarding traffic safety may differ from one country to another, the findings from this study could serve as a basis for understanding and improving traffic safety on both sealed and unsealed pavements around the world. Several limitations should be noted in this study. First, this study used police-reported data and may be subject to underreporting. Secondly, our study used data spanning 2015 to 2018, which is not very current. Besides, the study only explored the transferability of data based on the type of pavement (sealed and unsealed), and no temporal stability tests were considered. In the future, it would be worthwhile to consider more recent data and to explore the temporal stability of the data to identify the possible changing impact of risk factors on injury severity outcomes with time.

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.

Appendix

Table A1
Performance comparison between random parameter model with heterogenity in mean and random parameter with heterogenity in mean and variance model for unsealed pavement.

Model Statistics	Heterogenity in Mean and Variance model	Heterogeniemodelty in Mean
Log-likelihood at convergence	−946.59	−949.35
Log-likelihood at constant	−1388.63	−1397.6
McFadden Pseudo R-squared	0.32	0.20
AIC	1109.2	1978.7
Estimation based on N	1086	1086

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