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A population-based case-control study of the effect of sun glare on pedestrian fatalities in Taiwan

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Abstract

Introduction

Sun glare poses serious driving hazards and increases accident risks. Relatively few studies, however, have been conducted to examine the effects of sun glare on pedestrian fatalities, given that an accident has occurred.

Objectives

The primary objective of this study was to investigate the effect of sun glare on pedestrian fatalities.

Methods

Using the Taiwan National Traffic Crash Data and sunrise and sunset data from the National Oceanic and Atmospheric Association (NOAA) for the period 2003–2016, this study investigated whether sun glare results in pedestrian fatalities resulting from motor vehicle crashes. Pedestrian crashes were classified into glare-related (case) and nonglare-related crashes (control). To account for unobserved heterogeneity, mixed logit models were estimated to identify the determinants of pedestrian fatalities specifically in sun-glare–related crashes.

Results

Of the 100,411 pedestrians involved in crashes during 2003–2016, 13,355 and 87,056 cases of glare-related and nonglare-related crashes, respectively, were reported. Pedestrians involved in glare crashes tended to be more fatally injured than those in nonglare crashes. Other contributory factors to fatal injuries among pedestrians were older pedestrians, male drivers, older drivers, intoxicated motorists, rural roadways, car overtaking manoeuvres, a heavy vehicle as the crash partner, and sunset hours. Walking against traffic appeared to be beneficial in decreasing injury severity.

Conclusions

Sun glare was associated with pedestrian fatalities. Older pedestrians, male drivers, older drivers, and intoxicated motorists were prevalent determinants of pedestrian fatalities in glare-related crashes.

Keywords: Sun glare; Pedestrian fatalities; Crashes; Injury

Strengths and limitations of this study

- This is a comprehensive study using the linked data from the two datasets.
- Our results derived from the linked datasets can be more reliable than those using a single database alone.
- Limitations of this study include the data that are unavailable from the two datasets such as geographic characteristics.

Introduction

Driving is a highly visual task that involves visual function and processing for establishing the effective control over a vehicle.[1] Research[2 3] has suggested that bright sunlight was ideal for driving because it increases the contrast, resolution, and luminosity of the surrounding landscapes. As a result, drivers may misinterpret the speed at which the surrounding landscape is approaching and gauge their travel velocity to be illusively slow, which would in turn prompt drivers to compensate by accelerating.[4 5]

Generally, bright sunlight causes temporary blindness when the sun is at a relatively low altitude and its rays fall directly in an individual's line of sight (e.g., just after sunrise or before sunset when the sun is above the horizon). By using a simulator, Gray and Regan[6] assessed the driving performance in both the absence and presence of a simulated low sun. They reported that sun glare resulted in a significant reduction in the safety margin accepted by drivers; the mean number of crashes was significantly higher during conditions of glare than during those of without glare, and older drivers exhibited a significantly greater reduction in the safety margin than did younger drivers. Another simulation study was conducted by Theeuwes et al.[7], who reported that low glare sources resulted in participants (drivers) exhibiting a significant drop in the ability to detect simulated pedestrians along the roadside. Theeuwes et al.[7] also pointed out that older participants reduced their driving speed the most and exhibited the largest drop in successful pedestrian detection.

Churchill et al.[8] employed a geometric model for examining whether sun glare affects the speeds of drivers on roadways and concluded that changes in speed as a result of sun glare was a factor in highway congestion. Jurado-Piña and Pardillo

Mayora[9], in an attempt to investigate the maximum tolerable sun glare caused by the angle between the sun and driving direction, pointed out that glare occurs when there is a specific angular distance between the driver's line of sight and the sun; this angular distance is 19° for a 40-year-old driver and 25 ° for a 60-year-old driver. Anue[10] suggested that in general no sun glare occurs if the angular distance is greater than 25°.

Several studies have investigated whether a direct relationship exists between sun glare and crashes by using data from police report or hospital. In a longitudinal study of patients who had been hospitalised as a consequence of a motor-vehicle crash, Redelmeier and Raza[11] concluded that bright sunlight was associated with an increased risk of life-threatening motor-vehicle crashes in Canada. By analysing police-reported crash data from Arizona, Mitra and Washington[12] indicated that sun glare was a crucial omitted variable that could explain intersection crash occurrence and that including this variable improved the explanatory power of statistical models. By linking police-reported crash data from Arizona with sunrise and sunset data from NOAA, Mitra[3] concluded that the odds of glare causing a crash were higher at intersections with roadways running eastbound and westbound than at those running northbound and southbound. Mitra3 further indicated that rear-end and angle crashes at signalised intersections were affected by sun glare, and, furthermore, the severity of motorist injury was unaffected by sun glare. A study that analysed traffic-accident database of Chiba, Japan, Hagita and Mori[13] revealed a higher occurrence of crashes involving pedestrians or bicycles at intersections where the sun was below 45° above the horizon in the driving direction. Sun et al.[14], who analysed police-reported crash data in Edmonton, Canada, reported similar findings, concluding that sun glare significantly contributed to crash occurrence, especially at intersections. Furthermore, they also indicated that the effect of sun glare on crash occurrence during the mornings on eastbound roads and evenings on westbound roads was significantly greater during the spring and autumn months and that certain crash types (e.g., crashes related to signal violation, failure to yield to pedestrians/cyclists, improper turning, and lane changing) were more likely to occur during periods of sun glare. By analysing police-reported crash data, Choi and Singh[15] pointed out that elderly motorists tended to have a greater propensity for striking other vehicles in conditions of sun glare, especially on roadways that were not physically divided.

Based on our literature review, a significant gap remains in the comprehensive understanding of the relationship between sun glare and pedestrian fatalities, conditioned on that a pedestrian crash has occurred. The primary research hypothesis of the present study is that pedestrian injury severity increases in accordance with restricted visibility (i.e., sun glare). As a result, the primary aim of this study was to investigate whether sun glare is associated with pedestrian fatalities. This study also aimed to investigate the determinants of pedestrian fatalities specifically in crashes related to sun glare.

Materials and Methods

Data source

By using the Taiwan National Traffic Crash Data as well as sunrise and sunset data from the National Oceanic and Atmospheric Association (NOAA) for the period from 2003 to 2016 (National Oceanic Earth System Research Laboratory and Atmospheric Administration16. Accessed: 2018-08-22), the current study examined the effect of sun glare on pedestrian fatalities, given that an accident involving a vehicle and pedestrian has occurred. The Taiwan National Traffic Crash Data comprise two files: an accident file and a vehicle and victim file. Accident files contain general information on the times and dates of crashes; weather, road; and lighting conditions, and road type. Vehicle and victim files contain vehicle-related information, such vehicle type, manoeuvres, first point of impact, and orientation, as well as driver and casualty characteristics, such as age, sex, and injury severity. Injury severity is classified into two levels: fatality and injury. Victims who die within 24 h as a result of an accident are classified as cases of fatality, whereas victims who sustain injuries, whether mild or severe, are classified as cases of injury.

Data on daily sunrise and sunset times and orientation are available from the NOAA. The information on the sunrise and sunset orientation for Taiwan is presented in online supplementary appendix 1. By using the data on the temporal characteristics (i.e., time and date) and orientation of vehicle crashes from the Taiwan National Traffic Crash Data, pedestrian crashes were matched with the sunrise and sunset data of the NOAA and subsequently classified into glare-related or nonglare-related crashes.

A glare-related crash is defined as a crash in which the following conditions are satisfied: the car was travelling in a direction towards the sunrise or sunset, and the angular distance between the driver's line of sight and the sun was between 0° and 45°. The angular distances were adjusted according to the time of the crash (available from the National Traffic Crash Dataset) and daily sunrise and sunset times daily (available from the NOAA). For example, a crash in which a car driver headed northeast collided with a pedestrian at 06:18 (A.M.) on 18 June, 2016, was classified as a glare-related crash. Notably, the angular distances, ranging from 0° to 45°, were reported[13] to cause sun glare and potentially affect on traffic safety. We therefore adopted the angular distance, range of 0–45°, as the threshold for defining a glare-related crash.

A flow-chart of the sample selection from the Taiwan Traffic Crash Dataset for the period from 2003 to 2016 is presented in online supplementary Appendix 2. A total of 195,258 pedestrian casualties from traffic crashes were extracted from during this period. This study focused on pedestrian crashes where the crash partner was a motorcycle, car, taxi, heavy-goods vehicle, bus, or coach. Crashes that occurred during adverse weather conditions, such as rain or fog, were excluded (n = 45,712). A total of 917 cases had missing data with regard to accident date and time and vehicle orientation. Because these cases (adverse weather conditions and missing data) were not mutually exclusive, the total number of cases excluded was 45,365, yielding a total of 149,839 valid cases for pedestrian casualties. These valid cases were matched with the NOAA sunrise and sunset data. After excluding crashes that had occurred before sunrise and after sunset (n = 49,428), 100,411 cases of pedestrian causalities remained. Of the 100,411 pedestrians that were matched with the sunrise and sunset data from the NOAA, 13,355 were glare-related cases (treated as cases), and 87,056 were nonglare-related cases (treated as controls), respectively.

Definition of variables

The following demographic data were collected for casualties: sex, age (four groups: <18, 18–40, 41–64, and ≥ 65 years), alcohol use (yes: breathalyser test results ≥ 0.15 mL/L or blood-alcohol consumption [BAC] level > 0.03%; no: breathalyser test results < 0.15 mL/L or BAC level ≤ 0.03%), licence status (licensed: with a valid licence; or unlicensed: without a valid licence), and pedestrian crossing manner (facing traffic: pedestrians walking towards traffic; back to traffic: pedestrians walking back to the traffic; crossing: pedestrians crossing the street). In Taiwan, those under the age 18 are identified as teenagers who are unable to legally ride motorcycles or drive car. Those aged 65 years or older were identified as the elderly individual. For individuals aged 18–40 and 41–64, we classified the remaining ages into two even age intervals. BAC data were obtained by police who conducted breathalyser tests or followed up for blood tests at hospitals. According to Taiwanese law, drivers with either breathalyser test >= 0.15 mL/L or BAC level > 0.03% were considered to be drunk-driving. Data from breathalyser tests or BAC levels were available only for motorists not for pedestrians because, by law, only motorists involved in crashes are mandated to be tested for alcohol consumption.

The vehicle attribute considered was the crash partner (motorcycle, car, taxi, and heavy vehicles such as buses and coaches). The following road factors were considered: sun glare (yes: affected by sun glare; no: unaffected by sun glare) and crash location (rural: roadways with speed limits of ≥ 51km/h, and urban: roadways with speed limits of ≤ 50km/h). Two temporal factors, month of the crash (spring/summer: March–August or autumn/winter: September–February) and days of crash (weekday: Monday–Friday or weekend: Saturday–Sunday) were examined.

Statistical analysis

The distribution of pedestrian injury severity according to a set of variables (e.g., human attributes, environmental factors, and vehicle characteristics) is reported in this study. Chi-square tests were conducted to examine the association between the independent variables and pedestrian injury severity. Because the dependent variable was binary (fatal vs. injury), the binary mixed logit models, which allow parameter coefficients to have distribution rather than fixed across the individuals, were estimated. Using the chi-square tests, the variables discovered to be significantly associated with the outcome ($p < 0.2$) were then incorporated into the multivariate mixed logit models. To detect the multi-collinearity among the variables (all categorical), a chi-square independent test was conducted and Cramer's V[17] was estimated. To determine whether sun glare was associated with pedestrian fatalities, one overall model that includes sun glare as one of the variables was utilised. One additional model was subsequently estimated to investigate the determinants of pedestrian fatalities, specifically in sun-glare–related crashes.

Mixed logit models were estimated to account for unobserved heterogeneity that may have arisen as a consequence of unmeasured variables, such as risk perception, behavioural factors, and other socioeconomic factors not available in the crash data from police reports. One example of a behavioural factor is distraction by phone use that may result in risk-taking inclinations and consequently an increased risk of injury. [18 19] Ignoring the effects of unobserved variables may lead to inconsistent estimates in non-linear models. [20]

In the present study, the utility of the injury severity i for a crash n is defined as follows:

$$IS_{in} = \beta_n^{'} X_{in} + \varepsilon_{in} \qquad \text{Eq. (1)}$$

where IS_{in} is an injury-severity function determining the injury-severity category n (fatal or injury) for an individual pedestrian i, X_{in} is a vector of the observed variables, such as pedestrian and driver attributes, vehicle characteristics, and environmental or temporal variables, β_n is a vector of the parameters associated with X_{in}, and ε_{in} is the error term. The mixed logit model uses β_n as a vector of estimable parameters for the discrete outcome n, which varies across the observed pedestrians. The variation is observed with density $f(\beta|\theta)$, where θ is a vector of the parameters of the density distribution. In most applications, mixed models specify that the density f has a continuous distribution, such as a normal, lognormal, triangular, or uniform distribution.

Given error terms that are independent and identically Gumbel distributed[21], the unconditional probability of one alternative n (from the set of injury-severity categories I) is the integral of the conditional probability with a multinomial logit form over the parameter β of density f:

$$P_{in} = \int \left(\frac{\exp(\beta' X_{in})}{\sum_I \exp(\beta' X_{in})} \right) f(\beta|\theta) d\beta \qquad \text{Eq. (2)}$$

All parameters are first assumed to be random and then their estimated standard deviations are evaluated using a zero-based (asymptotic) *t*-test for each parameter. One study[20] pointed out that a simulation-based maximum likelihood with 200 Halton draws may provide a more efficient distribution of draws for numerical integration and requires fewer draws to achieve convergence. Attempts were made in the present study to obtain more significant results by increasing the number of Halton draws, and the results appeared stable with the use of 1000 Halton draws.

Results

Table 1 lists the distribution of pedestrian injury severity according to a set of variables. Of the 13,355 glare-related cases, 329 pedestrians (2.46%) sustained fatal injuries, which is higher than those in nonglare-related crashes (1.83%). Additionally, the majority of pedestrian crashes involved motorists with valid licences (85.65%), sober motorists (85.97%), urban roadways (89.57%), pedestrians who were hit while crossing the street (65.85%), and nonglare conditions (86.70%) and occurred on weekdays (74.83%).

Table 1: Distribution of pedestrian injury severity according to a set of variables for the period 2003–2016.

		Fatal	Injury	χ^2 test
	N	n(%)	n(%)	p-value
Total	100411	1925(1.92)	98486(98.08)	
Sun glare				
Yes	13355(13.30)	329(2.46)	13026(97.54)	<0.01
No	87056(86.70)	1596(1.83)	85460(98.17)	
Pedestrian gender				
Male	50942(50.73)	1015(1.99)	49927(98.01)	0.08
Female	49469(49.27)	910(1.84)	48559(98.16)	
Driver gender				<0.01
Male	53351(53.13)	1132(2.12)	52219(97.88)	
Female	47060(46.87)	793(1.69)	46267(98.31)	
Pedestrian age				
<18	3644(3.63)	67(1.84)	3577(98.16)	<0.01
18-40	25851(25.75)	154(0.60)	25697(99.40)	
41-64	31283(31.15)	352(1.13)	30931(98.87)	
≥65	39633(39.47)	1352(3.41)	38281(96.59)	

		Fatal	Injury	χ^2 test
	N	n(%)	n(%)	p-value
Driver age				
<18	4458(4.44)	103(2.31)	4355(97.69)	<0.01
18-40	25808(25.70)	295(1.14)	25513(98.86)	
41-64	32523(32.39)	474(1.46)	32049(98.54)	
≥65	37622(37.47)	1033(2.75)	36589(97.25)	
Driver licence				0.01
Licensed	86007(85.65)	1609(1.87)	84398(98.13)	
Unlicensed	14404(14.35)	316(2.19)	14088(97.81)	
Alcohol use for driver				
No	86322(85.97)	1512(1.75)	84810(98.25)	<0.01
Yes	14089(14.03)	413(2.93)	13676(97.07)	
Months				
Spring/summer	47671(47.48)	914(1.92)	46757(98.08)	0.99
Autumn/winter	52740(52.52)	1011(1.92)	51729(98.08)	
Crash location				
Rural	10475(10.43)	352(3.36)	10123(96.64)	<0.01
Urban	89936(89.57)	1573(1.75)	88363(98.25)	
Crash partner				
Motorcycle	33221(33.09)	643(1.94)	32578(98.06)	<0.01
Car	45963(45.77)	801(1.74)	45162(98.26)	
Taxi	9655(9.62)	208(2.15)	9447(97.85)	
Heavy vehicles	11572(11.52)	356(3.08)	11216(96.92)	
Pedestrian's movement				
Facing traffic	9704(9.66)	172(1.77)	9532(98.23)	<0.01
Back to traffic	24584(24.48)	623(2.53)	23961(97.47)	
Crossing	66123(65.85)	1130(1.71)	64993(98.29)	
Car's manoeuvre				
Straight	50836(50.63)	862(1.70)	49974(98.30)	<0.01
Changing lane	15625(15.56)	257(1.64)	15368(98.36)	
Overtaking	21339(21.25)	601(2.82)	20738(97.18)	
Turning	12611(12.56)	205(1.63)	12406(98.37)	
Weekdays				
Weekday	70366(70.08)	1267(1.80)	69099(98.20)	<0.01
Weekend	30045(29.92)	658(2.19)	29387(97.81)	

Using chi-square tests, the following variables were determined to be significantly associated with the outcome: sun glare; pedestrian and driver sex and age; driver license possession, alcohol consumption; crash month, location, and partner; pedestrian movement; car manoeuvre; and day of the week. These factors were then incorporated into the mixed logit models.

Table 2 presents the estimation results of the mixed logit model of pedestrian injury severity. Parameters that were determined to be random were those that produced statistically significant standard errors for the assumed distributions; in this study, random parameters were male motorists and heavy vehicle as crash partners, with a uniform distribution that appears to provide the best statistical fit.

Table 2: Mixed logit estimation results for pedestrian injury severity during the period 2003–2016 [a] (n = 100,411).

Variable	Parameter	Standard error	*t*-value
Fatal injury			
Fixed parameter			
Constant	−0.531	0.215	−2.47
Sun-glare–related crash	0.527	0.164	3.21
Pedestrians facing traffic	−0.304	0.110	−2.76
Pedestrians aged 65+	0.553	0.237	2.33
Motorists aged 65+	0.218	0.102	2.14
Rural roadways	0.985	0.251	3.92
Intoxicated motorist	0.606	0.213	2.85
Weekend	0.134	0.053	2.53
Car overtaking manoeuvre	0.472	0.132	3.58
Random parameter			
Male motorists			
Standard deviation of distribution	0.360	0.116	3.10
Male motorists			

Standard deviation of distribution	0.467	0.173	2.70

Restricted log-likelihood (constant only): −8,116.7

Log-likelihood at convergence: −5,867.2

ρ^2 =0.277

[a] The outcome “injury” is the baseline case with its parameters set at zero.

Considering the results listed in Table 2, sun-glare–related crashes was found to be significant, and the estimated parameter was fixed across the observed pedestrians (the standard error for this parameter, when allowed to be random, was statistically nonsignificant). The parameter implies that sun a sun-glared–related crash was more likely to result in fatal injuries among pedestrians than a nonglare–related crash. Other factors discovered to have fixed effects on observed pedestrians and increase the likelihood of fatal injuries were pedestrians aged 65 or older, motorists aged 65 years or older, rural roadways, intoxicated motorist, weekend, and car overtaking manoeuvre.

The parameter for the variable of male motorist appeared to be random, with a uniform distribution with a mean of 0 and standard deviation of 0.360 (see Table 2), indicating that individual pedestrians being struck by male motorists had different parameters. Given the estimates (a mean of 0 and standard deviation of 0.360), approximately half of all pedestrians have a higher probability of sustaining fatal injuries when all other variables remain constant. Another parameter found to have a nonlinear effect across the sample of pedestrians was the variable of a heavy vehicle as the crash partner (with a uniform distribution). This parameter had a mean of 0 and standard deviation of 0.467 (see Table 2), indicating that individual pedestrians struck by heavy vehicles have different parameters, with half of the distributions resulting in a positive parameter (increasing the likelihood of fatal injuries) and half resulting in negative parameter (decreasing the likelihood of fatal injuries). The non-uniformity of the effects of male motorists and heavy vehicles is likely a consequence of other unmeasured factors, such as driver experiences; for some male drivers or more experienced drivers operating heavy vehicles (factors would reduce the effect of sun glare), injuries sustained by pedestrians were likely to be minor once a crash had occurred.

The movement of pedestrians towards traffic was also discovered to be significantly affect pedestrian fatalities. This fixed parameter suggests that pedestrians who faced traffic while walking were less likely to sustain fatal injuries than those undertaking other movements, such as walking back to traffic or crossing the street.

Table 3 presents the estimation results of the mixed logit model of pedestrian injury severity specifically in sun-glare–related crashes. For this model, the only random parameter (with a uniform distribution) was significant for the variable of heavy vehicle as the crash partner. The heterogeneous effect indicates that certain crashes involving heavy vehicles were associated with both higher and lower likelihoods of pedestrians sustaining fatal injuries. We speculate that this heterogeneous effect may be caused by variance in the experience level among certain driver groups, with more experienced drivers exhibiting a decreased likelihood of causing fatal injuries. In other words, heavy vehicles are normally operated by professional drivers, with the majority of drivers in this group being men and middle-aged or older individuals. To confirm this speculation, the interaction between the variable of heavy vehicle and other variables, such as male and middle-aged or older motorists, were added to the model specification, but were dropped from the model because all were determined to be insignificantly different from zero at the 0.1 level. The heterogeneity identified for the variable of heavy vehicle presented another argument in favour of estimating a mixed logit model of pedestrian injury severity because such effects are difficult to identify when using a logit framework with numerous interaction terms.

Table 3: Mixed logit estimation results for pedestrian injury severity specifically for sun-glare–related crashes during the period 2003–2015 [a] (n = 13,355).

Variable	Parameter	Standard error	*t*-value
Fatal injury			
Fixed parameter			
Constant	−0.262	0.127	−2.06
Sunset	0.336	0.090	3.73
Pedestrians facing traffic	−0.417	0.112	−3.72
Pedestrians aged 65+	0.510	0.183	2.79
Motorists aged 65+	0.468	0.137	3.42
Rural roadways	0.660	0.164	4.02
Car overtaking manoeuvre	0.367	0.107	3.43

Random parameter			
Heavy vehicle as crash partner			
Standard deviation of distribution	0.396	0.154	2.57

Restricted log-likelihood (constant only): −4,327.2

Log-likelihood at convergence: −3,286.5

ρ^2 =0.241

[a] The outcome "injury" is constituted the baseline, with its parameters set at zero

In this mixed logit model specifically for sun-glare–related crashes, the parameter for the variable sunset was discovered to be significant and fixed across the observed pedestrians. This parameter implies that injuries sustained by pedestrians were more likely to be fatal under sunset conditions than under sunrise conditions. Other fixed and significant factors that increased the likelihood of fatal injuries were pedestrians aged 65 or older, motorists aged 65 or older, rural roadways, and car overtaking manoeuvre. Similar to the overall mixed logit model of pedestrian injury severity, facing traffic in a glare-related crash was determined to be a protective factor in reducing pedestrian fatalities. This fixed parameter suggests that the effect of facing traffic on pedestrian injury severity was uniform across the observed pedestrians.

Discussions

By using the National Traffic Crash Data and sunrise and sunset data from the NOAA, the present study examined whether sun glare was associated with pedestrian fatalities involved in motor vehicle crashes. This research may constitute a valuable contribution to the growing literature on pedestrian safety as well as fill a major research gap regarding the effect of sun glare on pedestrian fatalities. Regarding methodological contributions, the proposed models offer methodological flexibility for identifying individual-specific heterogeneity that may arise as a result of other unmeasured factors related to motorist experience, behaviour, and geometric characteristics. When developing intervention strategies for improving pedestrian safety in sun-glare conditions, the heterogeneous effects of certain variables (which cannot be uncovered by using traditional logit models) should be considered.

The empirical contributions of this research comprise those research findings that are related to the factors affecting pedestrian fatalities. The identification of these risk factors may provide policy-makers with information for establishing suitable policies and strategies that may further reduce the risk of crashes in general or severity in particular. The following findings merit further discussion.

Most drivers commute during hours of extreme sun glare. It is therefore not surprising that more crashes occurs on roadways where there is a significant portion of traffic during peak morning (sunrise) and afternoon (sunset) hours. The adverse effect of sun glare on crash occurrence has been well documented in relevant literature.[3 14] Mitra[3] pointed out that motorist injury severity, however, was not increased in glare conditions, possibly as a consequence of reduced travel speed.[8] Such a protective effect of sun glare on the associated motorist injury severity does not apply to pedestrians; our study concludes that glare conditions (as indicated in the overall model) were associated with pedestrian fatalities. In our study, it is evident that this adverse effect of sun glare was greater on rural roadways where collision impacts can be higher and motorists may not expect to encounter a pedestrian as much as they would on urban roadways. One commonly-adopted engineering measure is the use of variable message signs to warn drivers of the risk of sun glare at the times when and locations (i.e., rural roadways) where sun-glare conditions occur.[9]

Mitra[3] pointed out that the odds of glare causing crashes at intersections were higher during the morning hours, and in autumn and winter months in Arizona, United States. In our study, the effect of seasons on pedestrian fatalities was not significant. Adding to the research conducted by Hagita and Mori[22], who concluded that the rate of pedestrian crashes shortly after sunset was higher than that of any other time in Japan, our study revealed that compared with sunrise times, the adverse effect of sun glare on pedestrian fatalities was greater during sunset hours in Taiwan. It is therefore evident here that sun glare during the sunset hours may not only increase pedestrian crashes, as indicated by Hagita and Mori[22], but also the resulting injury severity.

384 Studies have suggested that intoxicated motorists were more likely to leave pedestrians unattended by leaving the crash scene, thereby increasing pedestrian injury severity; and furthermore, alcohol use has been discovered to be a more prevalent factor for hit-and-runs at nights and during the weekend.[23 24] Our study revealed that the combined effects of alcohol consumption and sun glare were associated with pedestrian fatalities. Similar to other studies[23 24], our research highlights, in particular, the effect of motorist alcohol consumption on fatal injuries and on the weekends.

392 Other studies have consistently reported that elderly motorists were the group most affected by sun glare. For example, two simulation studies conducted by Gray and Regan[6] and Theeuwes et al.[7] reported that in conditions of sun glare, older drivers executing a turning manoeuvre demonstrated a significantly greater reduction in safety margin than did younger drivers; and older drivers demonstrated the most significant decrease in the ability to successfully detect pedestrians. Studies analysing real-life police-reported crash data[15] have indicated that in conditions of sun glare, older drivers were more likely to strike other vehicles. Our study contributes to the literature on pedestrian safety literature by concluding that older motorists, when affected by sun glare, cause fatal injuries to pedestrians once a crash has occurred. Advance warning signs or educational efforts to increase older driver's awareness of

sun-glare conditions may either temper the likelihood of vehicle crashes or reduce pedestrian injury severity.

Considerable work has consistently concluded that older pedestrians were more likely to be fatally or severely injured in crashes, both during daytime and night conditions.[25] Our research has provided ample evidence to suggest that injuries sustained by older pedestrians in crashes caused by sun glare are more fatal than those sustained by younger pedestrians. It is unclear whether the reduced conspicuity of pedestrians (particularly older pedestrians) under conditions of sun glare (twilight) plays a role in this effect. However, enhancing the conspicuity of pedestrians through the use of visibility aids, not only in night conditions[26] but also in twilight conditions, may be beneficial for reducing crash risk or severity.

Adding to the research conducted by Sun et al.[14], who reported that crashes related to improper turning or lane changing were more likely to occur during periods of sun glare, this present study concludes that an association exists between the execution of overtaking manoeuvres during periods of sun glare and pedestrian fatalities. It is not uncommon for injuries sustained in crashes caused by vehicle overtaking to be severe because motorists must accelerate to overtake other vehicles. In Taiwan, it is common that motorists execute overtaking manoeuvres by using roadway shoulders where there are pedestrians. Motorists should be aware of the risk they pose to pedestrians when overtaking other vehicles, particularly during periods of sun glare.

Studies have reported that facing traffic is beneficial for preventing pedestrian crashes[27] and decreasing the severity of related injuries[25]. Our study complements these two studies by concluding that walking against the traffic was associated with decreased injury severity. Information expressing the necessity facing traffic while walking along a street, particularly in conditions of sun glare, should be supplemented with specific information regarding its safety benefits.

Although differing for observed pedestrians, being struck by heavy vehicles increased the likelihood of fatal injuries. Although this finding agrees with those of other studies[28 29] reporting the tendency of injuries sustained by pedestrians to be fatal or more severe when struck by a heavy vehicle, we concluded that the effect of heavy vehicles was greater in conditions of sun glare. Notably, drivers of heavy vehicles tend to be professional. It is unclear whether drivers of this particular group, in combination with undertaking longer hours of travel than those undertaken by a car driver, are more susceptible to problems related to sun glare. Educational efforts can be directed towards drivers of heavy vehicles regarding their susceptibility to sun glare, and on roadways with pedestrians in particular.

This study had the following research limitations. First, our study did not consider surrounding topography; it is possible that motorists travelling through some areas with buildings or mountains, for example, are less susceptible to sun glare because the sun is occluded. By analysing geographic data and data from police reports, likely locations for sun glare can be predicted, and motorists can be well informed regarding where to expect sun glare. Furthermore, we classified a crash as being glare-related when the angular distance between the driver's line of sight and the sun was between 0° and 45°. Further investigations should be conducted concerning the angular distances at which sun glare affects motorists, as well as the variance of this effect for motorists of different ages, as indicated by Jurado-Piña and Pardillo Mayora[9]. Indeed, sun glare is a combined spatial-temporal factor. To broaden our collective understanding of factors in pedestrian safety, it is paramount that additional spatial data and temporal data be collected and compared whenever possible. Finally, the empirical results obtained in this study may be unique to Taiwan because of its unique sunrise and sunset times and orientations. As a result, until additional analyses are conducted using data from other jurisdictions to determine whether sun glare is a salient factor to pedestrian fatalities, caution should be exercised in generalising our findings for application in other settings.

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461 The authors declare to have no conflict of interests.

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464 The data sources used in the present study were the National Traffic Accident Dataset
465 and the NOAA.

466

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468

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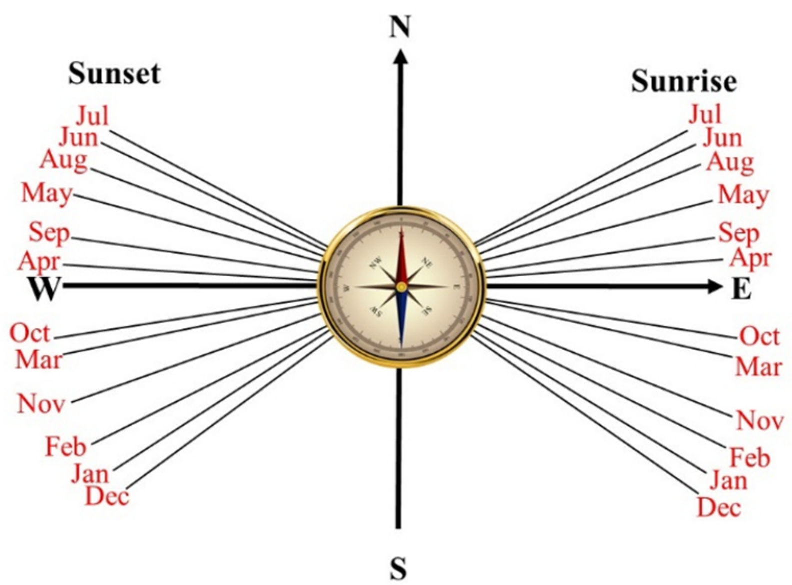
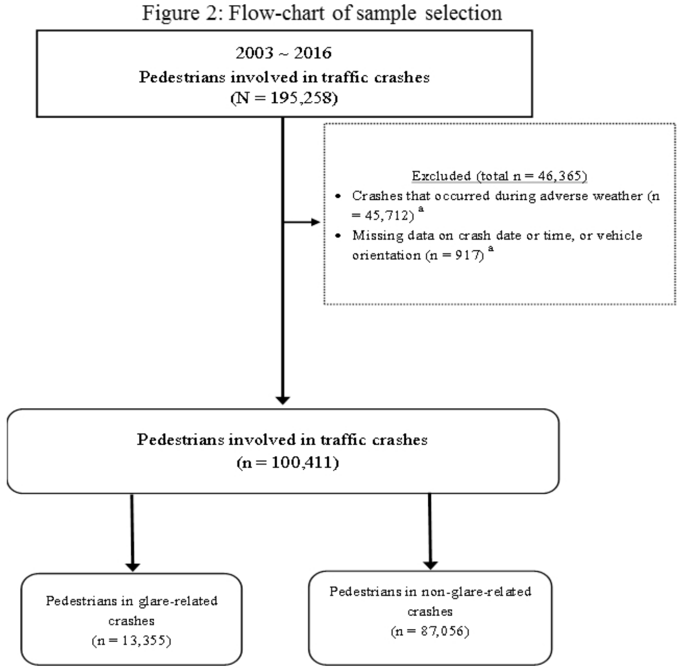
Appendix 1: Directions of sunrise and sunset in Taiwan



254x190mm (96 x 96 DPI)

Figure 2: Flow-chart of sample selection



[a] Because these cases were not mutually exclusive, the total number of cases excluded was 46,365.

254x190mm (96 x 96 DPI)

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A population-based case-control study of the effect of sun glare on pedestrian fatalities in Taiwan

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Abstract

Objectives Sun glare poses serious driving hazards and increases accident risks. Relatively few studies, however, have been conducted to examine the effects of sun glare on pedestrian fatalities, given that an accident has occurred. The primary objective of this study was to investigate the effect of sun glare on pedestrian fatalities.

Design A population-based case-control study.

Setting Taiwan.

Participants Using the Taiwan National Traffic Crash Data and sunrise and sunset data from the National Oceanic and Atmospheric Association (NOAA) for the period 2003–2016, 100,411 pedestrians involved in crashes were identified. Of these crashes, there were 13,355 and 87,056 cases of glare-related (case) and nonglare-related (control) crashes, respectively.

Methods To account for unobserved heterogeneity, mixed logit models were estimated to identify the determinants of pedestrian fatalities.

Main outcome measures Pedestrian fatalities.

Results Pedestrians involved in glare crashes were more likely to be fatally injured

than those in nonglare crashes. Other contributory factors to fatal injuries among pedestrians were older pedestrians, male drivers, older drivers, intoxicated motorists, rural roadways, car overtaking manoeuvres, a heavy vehicle as the crash partner, and sunset hours. Walking against traffic appeared to be beneficial in decreasing injury severity.

Conclusions Sun glare was associated with pedestrian fatalities. Older pedestrians, male drivers, older drivers, and intoxicated motorists were prevalent determinants of pedestrian fatalities in glare-related crashes.

Keywords: Sun glare; Pedestrian fatalities; Crashes; Injury

Strengths and limitations of this study

- This is the first nationwide population-based case-control study to investigate the associations between pedestrian fatalities and sun glare.
- The large population-based dataset minimises selection bias.
- Glare-related crashes were defined by adjusting vehicle travel direction and daily times and orientations of sunrise and sunset.
- Limitations of this study include the data that are unavailable from the two datasets such as geographic characteristics.

Introduction

Driving is a highly visual task that involves visual function and processing for establishing the effective control over a vehicle.[1] Research[2 3] has suggested that bright sunlight was ideal for driving because it increases the contrast, resolution, and luminosity of the surrounding landscapes. As a result, drivers may misinterpret the speed at which the surrounding landscape is approaching and gauge their travel velocity to be illusively slow, which would in turn prompt drivers to compensate by accelerating.[4 5]

Generally, bright sunlight causes temporary blindness when the sun is at a relatively low altitude and its rays fall directly in an individual's line of sight (e.g., just after sunrise or before sunset when the sun is above the horizon). By using a simulator, Gray and Regan[6] assessed the driving performance in both the absence and presence of a simulated low sun. They reported that sun glare resulted in a significant reduction in the safety margin accepted by drivers; the mean number of crashes was significantly higher during conditions of glare than during those of without glare, and older drivers exhibited a significantly greater reduction in the safety margin than did younger drivers. Another simulation study was conducted by Theeuwes et al.[7], who reported that low glare sources resulted in participants (drivers) exhibiting a significant drop in the ability to detect simulated pedestrians along the roadside. Theeuwes et al.[7] also pointed out that older participants reduced their driving speed the most and exhibited the largest drop in successful pedestrian detection.

Churchill et al.[8] employed a geometric model for examining whether sun glare affects the speeds of drivers on roadways and concluded that changes in speed as a result of sun glare was a factor in highway congestion. Jurado-Piña and Pardillo Mayora[9], in an attempt to investigate the maximum tolerable sun glare caused by the angle between the sun and driving direction, pointed out that glare occurs when there is a specific angular distance between the driver's line of sight and the sun; this angular distance is 19° for a 40-year-old driver and 25° for a 60-year-old driver. Anue[10] suggested that in general no sun glare occurs if the angular distance is greater than 25°.

Several studies have investigated whether a direct relationship exists between sun glare and crashes by using data from police report or hospital. In a longitudinal study of patients who had been hospitalised as a consequence of a motor-vehicle crash, Redelmeier and Raza[11] concluded that bright sunlight was associated with an increased risk of life-threatening motor-vehicle crashes in Canada. By analysing police-reported crash data from Arizona, Mitra and Washington[12] indicated that sun glare was a crucial omitted variable that could explain intersection crash occurrence

96 and that including this variable improved the explanatory power of statistical models. 97 By linking police-reported crash data from Arizona with sunrise and sunset data from 98 NOAA, Mitra[3] concluded that the odds of glare causing a crash were higher at 99 intersections with roadways running eastbound and westbound than at those running 100 northbound and southbound. Mitra[3] further indicated that rear-end and angle crashes 101 at signalised intersections were affected by sun glare, and, furthermore, the severity of 102 motorist injury was unaffected by sun glare. A study that analysed traffic-accident 103 database of Chiba, Japan, Hagita and Mori[13] revealed a higher occurrence of crashes 104 involving pedestrians or bicycles at intersections where the sun was below 45° above 105 the horizon in the driving direction. Sun et al.[14], who analysed police-reported crash 106 data in Edmonton, Canada, reported similar findings, concluding that sun glare 107 significantly contributed to crash occurrence, especially at intersections. Furthermore, 108 they also indicated that the effect of sun glare on crash occurrence during the 109 mornings on eastbound roads and evenings on westbound roads was significantly 110 greater during the spring and autumn months and that certain crash types (e.g., crashes 111 related to signal violation, failure to yield to pedestrians/cyclists, improper turning, 112 and lane changing) were more likely to occur during periods of sun glare. By 113 analysing police-reported crash data, Choi and Singh[15] pointed out that elderly 114 motorists tended to have a greater propensity for striking other vehicles in conditions

115 of sun glare, especially on roadways that were not physically divided.

116 Based on our literature review above, a significant gap remains in the
117 comprehensive understanding of the relationship between sun glare and pedestrian
118 fatalities, conditioned on that a pedestrian crash has occurred. The primary research
119 hypothesis of the present study is that pedestrian injury severity increases in
120 accordance with restricted visibility (i.e., sun glare). As a result, the primary aim of
121 this study was to investigate whether sun glare is associated with pedestrian fatalities.
122 This study also aimed to investigate the determinants of pedestrian fatalities
123 specifically in crashes related to sun glare.

124

125 **Materials and Methods**

126 *Data source*

127 By using the Taiwan National Traffic Crash Data as well as sunrise and sunset data
128 from the National Oceanic and Atmospheric Association (NOAA) for the period from
129 2003 to 2016 (National Oceanic Earth System Research Laboratory and Atmospheric
130 Administration[16]. Accessed: 2018-08-22), the current study examined the effect of sun
131 glare on pedestrian fatalities, given that an accident involving a vehicle and pedestrian
132 has occurred. The Taiwan National Traffic Crash Data comprise two files: an accident
133 file and a vehicle and victim file. Accident files contain general information on the

times and dates of crashes; weather, road; and lighting conditions, and road type. Vehicle and victim files contain vehicle-related information, such vehicle type, manoeuvres, first point of impact, and orientation, as well as driver and casualty characteristics, such as age, sex, and injury severity. Injury severity is classified into two levels: fatality and injury. Victims who die within 24 h as a result of an accident are classified as cases of fatality, whereas victims who sustain injuries, whether mild or severe, are classified as cases of injury.

Data on daily sunrise and sunset times and orientation are available from the NOAA. The information on the sunrise and sunset orientation for Taiwan is presented in online supplementary appendix 1. By using the data on the temporal characteristics (i.e., time and date) and orientation of vehicle crashes from the Taiwan National Traffic Crash Data, pedestrian crashes were matched with the sunrise and sunset data of the NOAA and subsequently classified into glare-related or nonglare-related crashes. The Institutional Review Board that is affiliated with Taipei Medical University approved our study (IRB#: N201808071). Personal identification data such as name or identification number are not available in the dataset.

A glare-related crash is defined as a crash in which the following conditions are satisfied: the car was travelling in a direction towards the sunrise or sunset, and the angular distance between the driver's line of sight and the sun was between 0° and

45°. Data on vehicle's travel path (north, south, east, or west) are available from the National Traffic Crash Dataset; and data on sun directions are available from the NOAA. The angular distances were adjusted according to the time of the crash (available from the National Traffic Crash Dataset) and daily sunrise and sunset times daily (available from the NOAA). For example, according to the Taiwan National Traffic Crash Data, a car–pedestrian crash took place in Hsinchu City, where a car heading to northeast collided with a pedestrian at 06:18 (A.M.) on 18 June, 2016. The angular distances, ranging from 0° to 45°, were reported[13] in Japan to cause sun glare and potentially affect traffic safety. We adopted the angular distance, range of 0–45°, as the threshold for defining a glare-related crash. According to the NOAA website, for this particular timing (18 June, 2016) and location (Hsinchu City with latitude of 24.778 and longitude of 120.988), the sun rose from northeast, and the apparent sunrise and sunset times were at 05:07 and 18:47, respectively. The daytime length for this particular day is 13 hours and 40 mins, which is equivalent to 820 mins. The angular distances for sunrise and sunset are 0–180°; for this particular day, the sun moved 0.2195° every min (180/820=0.2195). The adopted angular distance of 45° is equivalent to 205 mins (45/0.2195=205); as such, the transformed angular distance of 0–45°for this particular crash is between 05:07 to 08:32 that has a difference of 205 mins. This particular crash was therefore classified as a glared–related crash because the car headed to northeast (which was the direction of the sunrise) and the time of the crash (06:18) falls into the angular distance of 0–45° (i.e., between 05:07 and 08:32).

A flow-chart of the sample selection from the Taiwan Traffic Crash Dataset for the period from 2003 to 2016 is presented in online supplementary Appendix 2. A total of 195,258 pedestrian casualties from traffic crashes were extracted from during this period. This study considered only pedestrian crashes where the crash partner was a motorcycle, car, taxi, heavy-goods vehicle, bus, or coach. Crashes that occurred during adverse weather conditions, such as rain or fog, or when it was cloudy, were excluded (n = 45,712). A total of 917 cases had missing data with regard to accident date and time and vehicle orientation. Because these cases (adverse weather conditions and missing data) were not mutually exclusive, the total number of cases excluded was 45,365, yielding a total of 149,839 valid cases for pedestrian casualties. These valid cases were matched with the NOAA sunrise and sunset data. After excluding crashes that had occurred after sunset and before sunrise (n = 49,428), 100,411 cases of pedestrian causalities remained. Of the 100,411 pedestrians that were matched with the sunrise and sunset data from the NOAA, 13,355 were glare-related cases (treated as cases), and 87,056 were nonglare-related cases (treated as controls), respectively.

Definition of variables

The following demographic data were collected for casualties: sex, age (four groups: <18, 18–40, 41–64, and ≥ 65 years), alcohol use (yes: breathalyser test results ≥ 0.15 mg/L or blood-alcohol concentration [BAC] level > 0.03%; no: breathalyser test results < 0.15 mg/L or BAC level ≤ 0.03%), licence status (licensed: with a valid licence; or unlicensed: without a valid licence), and pedestrian crossing manner (facing traffic: pedestrians walking towards traffic; back to traffic: pedestrians walking back to the traffic; crossing: pedestrians crossing the street). In Taiwan, those under the age 18 are identified as teenagers who are unable to legally ride motorcycles or drive car. Those aged 65 years or older were identified as the elderly individual. For individuals aged 18–40 and 41–64, we classified the remaining ages into two even age intervals. BAC data were obtained by police who conducted breathalyser tests or followed up for blood tests at hospitals. According to Taiwanese law, drivers with either breathalyser test >= 0.15 mg/L or BAC level > 0.03% were considered to be drunk-driving. Data from breathalyser tests or BAC levels were available only for motorists not for pedestrians because, by law, only motorists involved in crashes are mandated to be tested for alcohol consumption.

The vehicle attribute considered was the crash partner (motorcycle, car, taxi, and heavy vehicles such as buses and coaches). The following road factors were considered: sun glare (yes: affected by sun glare; no: unaffected by sun glare) and crash location (rural: roadways with speed limits of ≥ 51km/h, and urban: roadways with speed limits of ≤ 50km/h). Two temporal factors, month of the crash (spring/summer: March–August or autumn/winter: September–February) and days of crash (weekday: Monday–Friday or weekend: Saturday–Sunday) were examined.

Patient and Public Involvement

The current research analysed national police-reported crash data as well as sunrise and sunset data from the National Oceanic and Atmospheric Association, which are anonymised datasets. Patients and or public were not involved in this study.

Statistical analysis

The distribution of pedestrian injury severity according to a set of variables (e.g., human attributes, environmental factors, and vehicle characteristics) is reported in this study. Chi-square tests were conducted to examine the association between the independent variables and pedestrian injury severity. Because the dependent variable was binary (fatal vs. injury), the binary mixed logit models, which allow parameter coefficients to have distribution rather than fixed across the individuals, were estimated. Using the chi-square tests, the variables discovered to be significantly associated with the outcome ($p < 0.2$) were then incorporated into the multivariate mixed logit models. To detect the multi-collinearity among the variables (all categorical), a chi-square independent test was conducted and Cramer's V[17] was estimated. To determine whether sun glare was associated with pedestrian fatalities, one overall model that includes sun glare as one of the variables was utilised. One additional model with interaction terms of sun-glare–related crashes with other variables was subsequently estimated.

Mixed logit models were estimated to account for unobserved heterogeneity that may have arisen as a consequence of unmeasured variables, such as risk perception, behavioural factors, and other socioeconomic factors not available in the crash data from police reports. One example of a behavioural factor is distraction by phone use that may result in risk-taking inclinations and consequently an increased risk of injury. [18] [19] Ignoring the effects of unobserved variables may lead to inconsistent estimates to all statistical models.[20]

In the present study, the utility of the injury severity *i* for a crash *n* is defined as follows:

$$IS_{in} = \beta_n^{'} X_{in} + \varepsilon_{in} \qquad \text{Eq. (1)}$$

where IS_{in} is an injury-severity function determining the injury-severity category *i* (fatal or injury) for an individual pedestrian n, X_{in} is a vector of the observed variables, such as pedestrian and driver attributes, vehicle characteristics, and environmental or temporal variables, β_n is a vector of the parameters associated with X_{in}, and ε_{in} is the error term. The mixed logit model uses β_n as a vector of estimable parameters, which varies across the observed pedestrians. The variation is observed with density $f(\beta/\theta)$, where θ is a vector of the parameters of the density distribution. In most applications, mixed models specify that the density f has a continuous distribution, such as a normal, lognormal, triangular, or uniform distribution.

Given error terms that are independent and identically Gumbel distributed[21], the unconditional probability of one alternative i (from the set of injury-severity categories I) is the integral of the conditional probability with a multinomial logit form over the parameter β of density f:

$$P_{in} = \int \left(\frac{\exp(\beta' X_{in})}{\sum_{j=1}^{I} 1 + \exp(\beta' X_{nj})} \right) f(\beta|\theta) d\beta \qquad \text{Eq. (2)}$$

All parameters are first assumed to be random and then their estimated standard deviations are evaluated using a zero-based (asymptotic) t-test for each parameter. One study[20] pointed out that a simulation-based maximum likelihood with 200 Halton draws may provide a more efficient distribution of draws for numerical integration and requires fewer draws to achieve convergence. Attempts were made in the present study to obtain more significant results by increasing the number of Halton draws, and the results appeared stable with the use of 1000 Halton draws.

Results

Table 1 lists the distribution of pedestrian injury severity according to a set of variables. Of the 13,355 glare-related cases, 329 pedestrians (2.46%) sustained fatal injuries, which is higher than those in nonglare-related crashes (1.83%). Additionally, the majority of pedestrian crashes involved motorists with valid licences (85.65%), sober motorists (85.97%), urban roadways (89.57%), pedestrians who were hit while crossing the street (65.85%), and nonglare conditions (86.70%) and occurred on weekdays (74.83%).

Table 1: Distribution of pedestrian injury severity according to a set of variables for the period 2003–2016.

		Fatal	Injury	χ^2 test
	N	n(%)	n(%)	p-value
Total	100411	1925(1.92)	98486(98.08)	
Sun glare				
Yes	13355(13.30)	329(2.46)	13026(97.54)	<0.01
No	87056(86.70)	1596(1.83)	85460(98.17)	
Pedestrian gender				
Male	50942(50.73)	1015(1.99)	49927(98.01)	0.08
Female	49469(49.27)	910(1.84)	48559(98.16)	

	N	Fatal n(%)	Injury n(%)	χ^2 test p-value
Driver gender				
Male	53351(53.13)	1132(2.12)	52219(97.88)	<0.01
Female	47060(46.87)	793(1.69)	46267(98.31)	
Pedestrian age				
<18	3644(3.63)	67(1.84)	3577(98.16)	<0.01
18-40	25851(25.75)	154(0.60)	25697(99.40)	
41-64	31283(31.15)	352(1.13)	30931(98.87)	
≥65	39633(39.47)	1352(3.41)	38281(96.59)	
Driver age				
<18	4458(4.44)	103(2.31)	4355(97.69)	<0.01
18-40	25808(25.70)	295(1.14)	25513(98.86)	
41-64	32523(32.39)	474(1.46)	32049(98.54)	
≥65	37622(37.47)	1033(2.75)	36589(97.25)	
Driver licence				
Licensed	86007(85.65)	1609(1.87)	84398(98.13)	0.01
Unlicensed	14404(14.35)	316(2.19)	14088(97.81)	
Alcohol use for driver				
No	86322(85.97)	1512(1.75)	84810(98.25)	<0.01
Yes	14089(14.03)	413(2.93)	13676(97.07)	
Months				
Spring/summer	47671(47.48)	914(1.92)	46757(98.08)	0.99
Autumn/winter	52740(52.52)	1011(1.92)	51729(98.08)	
Crash location				
Rural	10475(10.43)	352(3.36)	10123(96.64)	<0.01
Urban	89936(89.57)	1573(1.75)	88363(98.25)	
Crash partner				
Motorcycle	33221(33.09)	643(1.94)	32578(98.06)	<0.01
Car	45963(45.77)	801(1.74)	45162(98.26)	
Taxi	9655(9.62)	208(2.15)	9447(97.85)	
Heavy vehicles	11572(11.52)	356(3.08)	11216(96.92)	
Pedestrian's movement				
Facing traffic	9704(9.66)	172(1.77)	9532(98.23)	<0.01
Back to traffic	24584(24.48)	623(2.53)	23961(97.47)	
Crossing	66123(65.85)	1130(1.71)	64993(98.29)	
Car's manoeuvre				
Straight	50836(50.63)	862(1.70)	49974(98.30)	<0.01

	N	Fatal n(%)	Injury n(%)	χ^2 test p-value
Changing lane	15625(15.56)	257(1.64)	15368(98.36)	
Overtaking	21339(21.25)	601(2.82)	20738(97.18)	
Turning	12611(12.56)	205(1.63)	12406(98.37)	
Sunset				
Sunset	8325(8.29)	214(2.57)	8109(97.41)	<0.01
Other daytimes	87056(86.70)	1596(1.83)	85460(98.17)	
Sunrise	5030(5.01)	115(2.29)	4915(97.71)	
Weekdays				
Weekday	70366(70.08)	1267(1.80)	69099(98.20)	<0.01
Weekend	30045(29.92)	658(2.19)	29387(97.81)	

Using chi-square tests, the following variables were determined to be significantly associated with the outcome: sun glare; pedestrian and driver sex and age; driver license possession, alcohol consumption; crash month, location, and partner; pedestrian movement; car manoeuvre; sunset hours; and day of the week. These factors were then incorporated into the mixed logit models.

Table 2 presents the estimation results of the mixed logit model of pedestrian injury severity. Parameters that were determined to be random were those that produced statistically significant standard errors for the assumed distributions; in this study, random parameters were male motorists and heavy vehicle as crash partners, with a uniform distribution that appears to provide the best statistical fit.

Table 2: Mixed logit estimation results for pedestrian injury severity during the period 2003–2016 [a] (n = 100,411).

Variable	Parameter	Standard error	*t*-value

Fatal injury			
Fixed parameter			
Constant	−0.531	0.215	−2.47
Sun-glare–related crash	0.527	0.164	3.21
Pedestrians facing traffic	−0.304	0.110	−2.76
Pedestrians aged 65+	0.553	0.237	2.33
Motorists aged 65+	0.218	0.102	2.14
Rural roadways	0.985	0.251	3.92
Intoxicated motorist	0.606	0.213	2.85
Weekend	0.134	0.053	2.53
Car overtaking manoeuvre	0.472	0.132	3.58
Sunset	0.162	0.074	2.19
Random parameter			
Male motorists	0.324	0.139	2.33
Standard deviation of distribution	0.389	0.163	2.39
Heavy vehicles	0.274	0.110	2.49
Standard deviation of distribution	0.622	0.290	2.14

Restricted log-likelihood (constant only): −8,267.1

Log-likelihood at convergence: −5,806.4

ρ^2=0.298

[a] The outcome “injury” is the baseline case with its parameters set at zero.

Considering the results listed in Table 2, sun-glare–related crashes was found to be significant, and the estimated parameter was fixed across the observed pedestrians (the standard error for this parameter, when allowed to be random, was statistically nonsignificant). The parameter implies that sun a sun-glared–related crash was more likely to result in fatal injuries among pedestrians than a nonglare–related crash. Other factors discovered to have fixed effects on observed pedestrians and increase the likelihood of fatal injuries were pedestrians aged 65 or older, motorists aged 65 years or older, rural roadways, intoxicated motorist, weekend, car overtaking manoeuvre, and sunset hours.

The parameter for the variable of male motorist appeared to be random, with a normal distribution with a mean of 0.324 and standard deviation of 0.389 (see Table 2), indicating that individual pedestrians being struck by male motorists had different parameters. Given the estimates (a mean of 0.324 and standard deviation of 0.389), approximately 79.8% of all pedestrians had a higher probability of sustaining fatal injuries when all other variables remain constant. Another parameter found to have a random effect across the sample of pedestrians was the variable of a heavy vehicle as the crash partner (with a normal distribution). This parameter had a mean of 0.274 and standard deviation of 0.622 (see Table 2), indicating that individual pedestrians struck by heavy vehicles have different parameters, with 67.0% of the distributions resulting in a positive parameter (increasing the likelihood of fatal injuries) and 33.0% resulting in negative parameter (decreasing the likelihood of fatal injuries).

The direction of travel of pedestrians relative to vehicular traffic was also discovered to significantly affect pedestrian fatalities. This fixed parameter suggests that pedestrians who faced traffic while walking were less likely to sustain fatal injuries than those undertaking other movements, such as walking back to traffic or crossing the street.

Table 3 presents the estimation results of the mixed logit model of pedestrian injury severity specifically in sun-glare–related crashes. For this model, the only random parameter (with a uniform distribution) was significant for the variable of heavy vehicle as the crash partner. The heterogeneous effect indicates that certain crashes involving heavy vehicles were associated with both higher and lower likelihoods of pedestrians sustaining fatal injuries. We speculate that this heterogeneous effect may be caused by variance in the experience level among certain driver groups, with more experienced drivers exhibiting a decreased likelihood of causing fatal injuries. In other words, heavy vehicles are normally operated by professional drivers, with the majority of drivers in this group being men and middle-aged or older individuals. To confirm this speculation, the interaction between the variable of heavy vehicle and other variables, such as male and middle-aged or older motorists, were added to the model specification, but were dropped from the model because all were determined to be insignificantly different from zero at the 0.1 level. The heterogeneity identified for the variable of heavy vehicle presented another argument in favour of estimating a mixed logit model of pedestrian injury severity because such effects are difficult to identify when using a logit framework with numerous interaction terms.

Table 3: Mixed logit estimation results for pedestrian injury severity with interaction terms of glare crashes and other variables [a] (n = 100,411)

Variable	Parameter	Standard error	*t*-value

Fatal injury			
Fixed parameter			
Constant	−0.324	0.139	−2.33
Male motorist	0.193	0.069	2.80
Sunset	0.274	0.089	3.08
Pedestrians facing traffic × glare crashes	−0.439	0.126	−3.48
Pedestrians aged 65+	0.533	0.210	2.54
Motorists aged 65+ × glare crashes	0.432	0.143	3.02
Rural roadways × glare crashes	0.684	0.190	3.60
Intoxicated motorist	0.461	0.154	2.99
Weekend	0.157	0.075	2.09
Car overtaking manoeuvre	0.329	0.121	2.72
Random parameter			
Heavy vehicle as crash partner	0.248	0.089	2.78
Standard deviation of distribution	0.526	0.211	2.49
Restricted log-likelihood (constant only): −7,302.7			
Log-likelihood at convergence: −5,054.6			
ρ^2=0.308			

[a] The outcome “injury” is constituted the baseline, with its parameters set at zero

This mixed logit model with the interaction term of glare crashes with other variables highlight several crucial features of glare crashes. For example, several interaction terms were discovered to be significant and fixed across the observed pedestrians, including facing traffic × glare crashes, elderly motorists × glare crashes, and rural roadways × glare crashes. It appears that facing traffic in a glare-related crash was determined to be a protective factor in reducing pedestrian fatalities. Injuries to pedestrians were more likely to be fatal in glare crashes in which the drivers were elderly. Furthermore, in glare crashes that took place in rural setting, injuries were more likely to be fatal than otherwise.

Discussions

By using the National Traffic Crash Data and sunrise and sunset data from the NOAA, the present study examined whether sun glare was associated with pedestrian fatalities involved in motor vehicle crashes. This research may constitute a valuable contribution to the growing literature on pedestrian safety as well as fill a major research gap regarding the effect of sun glare on pedestrian fatalities. Regarding methodological contributions, the proposed models offer methodological flexibility for identifying individual-specific heterogeneity that may arise as a result of other unmeasured factors related to motorist experience, behaviour, and geometric characteristics. When developing intervention strategies for improving pedestrian safety in sun-glare conditions, the heterogeneous effects of certain variables (which cannot be uncovered by using traditional logit models) should be considered.

The empirical contributions of this research comprise those research findings that are related to the factors affecting pedestrian fatalities. The identification of these risk factors may provide policy-makers with information for establishing suitable policies and strategies that may further reduce the risk of crashes in general or severity in particular. The following findings merit further discussion.

Most drivers commute during hours of extreme sun glare. It is therefore not surprising that more crashes occurs on roadways where there is a significant portion of traffic during peak morning (sunrise) and afternoon (sunset) hours. The adverse effect of sun glare on crash occurrence has been well documented in relevant literature.[3 14] Mitra[3] pointed out that motorist injury severity, however, was not increased in glare conditions, possibly as a consequence of reduced travel speed.[8] Such a protective effect of sun glare on the associated motorist injury severity does not apply to pedestrians; our study concludes that glare conditions (as indicated in the overall model) were associated with pedestrian fatalities. In our study, it is evident that this adverse effect of sun glare was greater on rural roadways where collision impacts can be higher and motorists may not expect to encounter a pedestrian as much as they would on urban roadways. One commonly-adopted engineering measure is the use of variable message signs to warn drivers of the risk of sun glare at the times when and locations (i.e., rural roadways) where sun-glare conditions occur.[9]

Mitra[3] pointed out that the odds of glare causing crashes at intersections were higher during the morning hours, and in autumn and winter months in Arizona, United States. In our study, the effect of seasons on pedestrian fatalities was not significant. Adding to the research conducted by Hagita and Mori[22], who concluded that the rate of pedestrian crashes shortly after sunset was higher than that of any other time in Japan, our study revealed that compared with sunrise times, the adverse effect of sun glare on pedestrian fatalities was greater during sunset hours in Taiwan. It is therefore evident here that sun glare during the sunset hours may not only increase pedestrian crashes, as indicated by Hagita and Mori[22], but also the resulting injury severity. Evening commute is often risky due to fatigue, distraction, or other unrelated factors to sun glare. In our study, we have found that injuries sustained by pedestrians were more likely to be fatal under sunset conditions than other daytime conditions. Additional research is warranted to examine whether sun glare affects pedestrian fatalities in evening commuting crashes.

Studies have suggested that intoxicated motorists were more likely to leave pedestrians unattended by leaving the crash scene, thereby increasing pedestrian injury severity; and furthermore, alcohol use has been discovered to be a more prevalent factor for hit-and-runs at nights and during the weekend.[23 24] Our study revealed that the combined effects of alcohol consumption and sun glare were associated with pedestrian fatalities. Similar to other studies[23 24], our research highlights, in particular, the effect of motorist alcohol consumption on fatal injuries and on the weekends.

Other studies have consistently reported that elderly motorists were the group most affected by sun glare. For example, two simulation studies conducted by Gray and Regan[6] and Theeuwes et al.[7] reported that in conditions of sun glare, older drivers executing a turning manoeuvre demonstrated a significantly greater reduction in safety margin than did younger drivers; and older drivers demonstrated the most significant decrease in the ability to successfully detect pedestrians. Studies analysing real-life police-reported crash data[15] have indicated that in conditions of sun glare, older drivers were more likely to strike other vehicles. Our study contributes to the literature on pedestrian safety literature by concluding that older motorists, when affected by sun glare, cause fatal injuries to pedestrians once a crash has occurred. Advance warning signs or educational efforts to increase older driver's awareness of sun-glare conditions may either temper the likelihood of vehicle crashes or reduce pedestrian injury severity.

In our study, no discrepancy was found when comparing injuries in spring/summer to autumn/winter. Such a result cannot be ascertained with any certainty. However, we speculate that this is primarily because the anticipated effect of sun glare in different seasons may be offset by, for example, tropical hurricanes that strike Taiwan in summer and northeast monsoon in winter. Our result here seems different to those in other studies conducted in large countries[3] where the adverse effect of sun glare was found to be greater in autumn and winter months. These studies were conducted in large countries such as the United States where climate changes significantly across areas with different latitudes, whereas Taiwan is a small country where climate does not change much across the small island.

Considerable work has consistently concluded that older pedestrians were more likely to be fatally or severely injured in crashes, both during daytime and night conditions.[25] Our research has provided ample evidence to suggest that injuries sustained by older pedestrians in crashes caused by sun glare are more fatal than those sustained by younger pedestrians. It is unclear whether the reduced conspicuity of pedestrians (particularly older pedestrians) under conditions of sun glare (twilight) plays a role in this effect. However, enhancing the conspicuity of pedestrians through the use of visibility aids, not only in night conditions[26] but also in twilight conditions, may be beneficial for reducing crash risk or severity.

Adding to the research conducted by Sun et al.[14], who reported that crashes related to improper turning or lane changing were more likely to occur during periods of sun glare, this present study concludes that an association exists between the execution of overtaking manoeuvres during periods of sun glare and pedestrian fatalities. It is not uncommon for injuries sustained in crashes caused by vehicle overtaking to be severe because motorists must accelerate to overtake other vehicles. In Taiwan, it is common that motorists execute overtaking manoeuvres by using roadway shoulders where there are pedestrians. Motorists should be aware of the risk they pose to pedestrians when overtaking other vehicles, particularly during periods of sun glare.

Studies have reported that facing traffic is beneficial for preventing pedestrian crashes[27] and decreasing the severity of related injuries[25]. Our study complements these two studies by concluding that walking against the traffic was associated with decreased injury severity. In these cases, it is possible that pedestrians' forward views are strongly lit, which might be more favourable for them than other directions. Information expressing the necessity facing traffic while walking along a street, particularly in conditions of sun glare, should be supplemented with specific information regarding its safety benefits.

Although differing for observed pedestrians, being struck by heavy vehicles increased the likelihood of fatal injuries. Although this finding agrees with those of other studies[28 29] reporting the tendency of injuries sustained by pedestrians to be fatal or more severe when struck by a heavy vehicle, we concluded that the effect of heavy vehicles was greater in conditions of sun glare. Notably, drivers of heavy vehicles tend to be professional. It is unclear whether drivers of this particular group, in combination with undertaking longer hours of travel than those undertaken by a car driver, are more susceptible to problems related to sun glare. Educational efforts can be directed towards drivers of heavy vehicles regarding their susceptibility to sun glare, and on roadways with pedestrians in particular.

This study had the following research limitations. First, our study did not consider surrounding topography; it is possible that motorists travelling through some areas with buildings or mountains, for example, are less susceptible to sun glare because the sun is occluded. By analysing geographic data and data from police reports, likely locations for sun glare can be predicted, and motorists can be well informed regarding where to expect sun glare. Furthermore, we classified a crash as being glare-related when the angular distance between the driver's line of sight and the sun was between 0° and 45°, a threshold based on the research in Japan[13]. Further research may attempt to compare our results to those adopting more stringent thresholds of 10, 20, or 30 degrees, as well as the variance of this effect for motorists of different ages, as indicated by Jurado-Piña and Pardillo Mayora[9]. Due to restricted funds, we were just able to link the National Traffic Crash Dataset to the NOAA, but not to pre-hospital triage system or hospital data (e.g., the National Health Insurance Research Dataset: NHIRD). We recommend that future research should link our data to clinical datasets that provide more details on injuries (e.g., injured body regions, hospitalisation) other than fatalities examined in the present paper.

Indeed, sun glare is a combined spatial-temporal factor. To broaden our collective understanding of factors in pedestrian safety, it is paramount that additional spatial data and temporal data be collected and compared whenever possible. Finally, the empirical results obtained in this study may be unique to Taiwan because of its unique sunrise and sunset times and orientations. As a result, until additional analyses are conducted using data from other jurisdictions to determine whether sun glare is a salient factor to pedestrian fatalities, caution should be exercised in generalising our findings for application in other settings.

Contributors: HPM drafted and revised the manuscript and established the theoretical supports for data analyses; PLC re-analysed the data and interpreted the results; SKC reviewed relevant literature and analysed the data; LHC analysed the data; VL edited the manuscript and reviewed relevant literature; CWP was responsible for study design, contributed to the analyzing and interpretation of data, drafted the manuscript, and strengthened discussions and conclusions. The final version of the manuscript was read and approved by each contributing author.

Competing interests: None declared.

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Data sharing statement: Only citizens of Taiwan who fulfill the requirements of conducting research projects are eligible to apply for the dataset. The use of dataset is limited to research purposes only. The authors had no special access privileges that others would not have.

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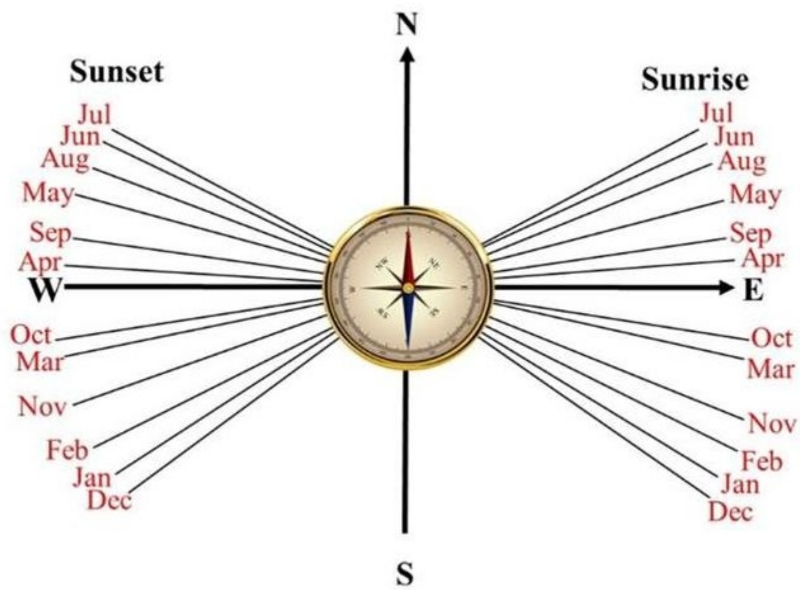
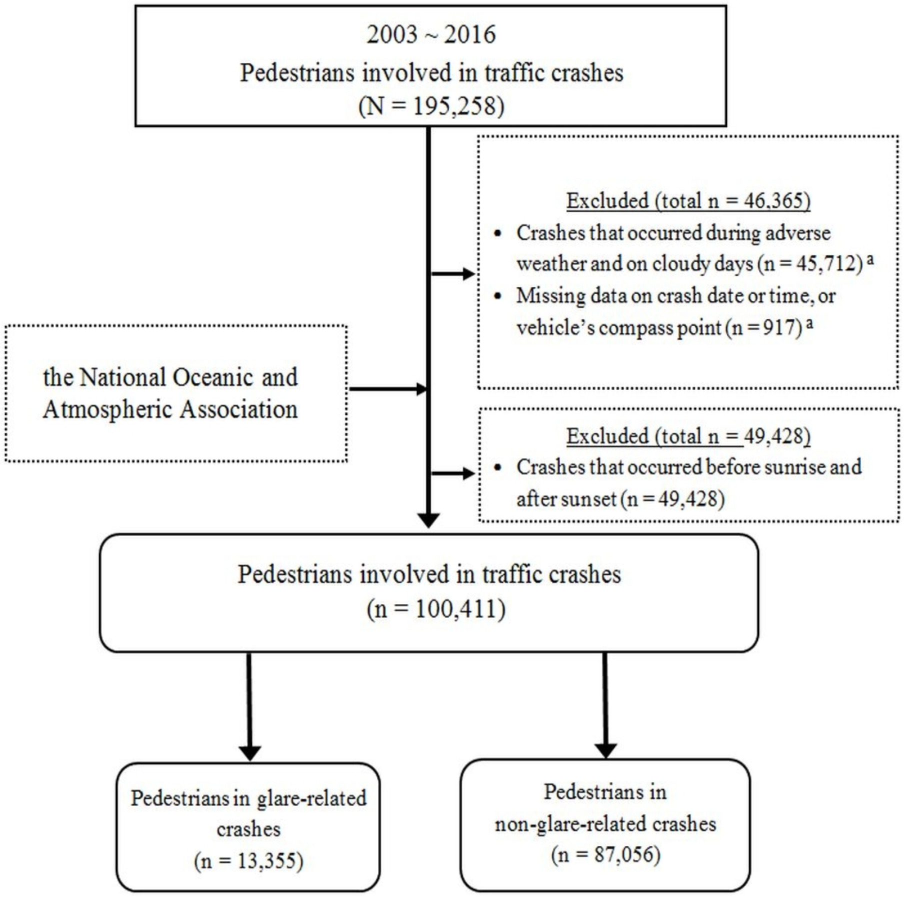
Appendix 1: Directions of sunrise and sunset in Taiwan



66x49mm (300 x 300 DPI)

Figure 2: Study flow chart



[a] As these cases were not mutually exclusive, the total cases excluded were 45,365.

90x90mm (300 x 300 DPI)

STROBE Statement

Checklist of items that should be included in reports of ***case-control studies***

Section/Topic	Item No	Recommendation	Reported on Page No
Title and abstract	1	(*a*) Indicate the study's design with a commonly used term in the title or the abstract	1
		(*b*) Provide in the abstract an informative and balanced summary of what was done and what was found	2–3
Introduction			
Background/rationale	2	Explain the scientific background and rationale for the investigation being reported	4–6
Objectives	3	State specific objectives, including any prespecified hypotheses	7
Methods			
Study design	4	Present key elements of study design early in the paper	8–10
Setting	5	Describe the setting, locations, and relevant dates, including periods of recruitment, exposure, follow-up, and data collection	8–12
Participants	6	(*a*) *Cohort study*—Give the eligibility criteria, and the sources and methods of selection of participants. Describe methods of follow-up *Case-control study*—Give the eligibility criteria, and the sources and methods of case ascertainment and control selection. Give the rationale for the choice of cases and controls *Cross-sectional study*—Give the eligibility criteria, and the sources and methods of selection of participants	7–9
		(*b*) *Cohort study*—For matched studies, give matching criteria and number of exposed and unexposed *Case-control study*—For matched studies, give matching criteria and the number of controls per case	
Variables	7	Clearly define all outcomes, exposures, predictors, potential confounders, and effect modifiers. Give diagnostic criteria, if applicable	11,12
Data sources/measurement	8*	For each variable of interest, give sources of data and details of methods of assessment (measurement). Describe comparability of assessment methods if there is more than one group	11,12
Bias	9	Describe any efforts to address potential sources of bias	9
Study size	10	Explain how the study size was arrived at	10
Quantitative variables	11	Explain how quantitative variables were handled in the analyses. If applicable, describe which groupings were chosen and why	11,12
Statistical methods	12	(*a*) Describe all statistical methods, including those used to control for confounding	12–15
		(*b*) Describe any methods used to examine subgroups and interactions	12–15
		(*c*) Explain how missing data were addressed	12–15
		(*d*) *Cohort study*—If applicable, explain how loss to follow-up was addressed *Case-control study*—If applicable, explain how matching of cases and controls was addressed *Cross-sectional study*—If applicable, describe analytical methods taking account of sampling strategy	12–15
		(*e*) Describe any sensitivity analyses	N/A

Section/Topic	Item No	Recommendation	Reported on Page No
Results			
Participants	13*	(a) Report numbers of individuals at each stage of study—eg numbers potentially eligible, examined for eligibility, confirmed eligible, included in the study, completing follow-up, and analysed	10
		(b) Give reasons for non-participation at each stage	10
		(c) Consider use of a flow diagram	Appendix 2
Descriptive data	14*	(a) Give characteristics of study participants (eg demographic, clinical, social) and information on exposures and potential confounders	10
		(b) Indicate number of participants with missing data for each variable of interest	10
		(c) *Cohort study*—Summarise follow-up time (eg, average and total amount)	N/A
Outcome data	15*	*Cohort study*—Report numbers of outcome events or summary measures over time	N/A
		Case-control study—Report numbers in each exposure category, or summary measures of exposure	N/A
		Cross-sectional study—Report numbers of outcome events or summary measures	15
Main results	16	(*a*) Give unadjusted estimates and, if applicable, confounder-adjusted estimates and their precision (eg, 95% confidence interval). Make clear which confounders were adjusted for and why they were included	15–21
		(*b*) Report category boundaries when continuous variables were categorized	N/A
		(*c*) If relevant, consider translating estimates of relative risk into absolute risk for a meaningful time period	N/A
Other analyses	17	Report other analyses done—eg analyses of subgroups and interactions, and sensitivity analyses	N/A
Discussion			
Key results	18	Summarise key results with reference to study objectives	22–29
Limitations	19	Discuss limitations of the study, taking into account sources of potential bias or imprecision. Discuss both direction and magnitude of any potential bias	27–29
Interpretation	20	Give a cautious overall interpretation of results considering objectives, limitations, multiplicity of analyses, results from similar studies, and other relevant evidence	27–29
Generalisability	21	Discuss the generalisability (external validity) of the study results	28–29
Other Information			
Funding	22	Give the source of funding and the role of the funders for the present study and, if applicable, for the original study on which the present article is based	29

**Give information separately for cases and controls in case-control studies and, if applicable, for exposed and unexposed groups in cohort and cross-sectional studies.*

Note: An Explanation and Elaboration article discusses each checklist item and gives methodological background and published examples of transparent reporting. The STROBE checklist is best used in conjunction with this article (freely available on the Web sites of PLoS Medicine at http://www.plosmedicine.org/, Annals of Internal Medicine at http://www.annals.org/, and Epidemiology at http://www.epidem.com/). Information on the STROBE Initiative is available at www.strobe-statement.org.

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Population-based case–control study of the effect of sun glare on pedestrian fatalities in Taiwan

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Population-based case–control study of the effect of sun glare on pedestrian fatalities in Taiwan

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Abstract

Objectives Sun glare is a serious driving hazard and increases crash risks. Relatively few studies have examined the effects of sun glare on pedestrian fatalities, given that a crash has occurred. The primary objective of this study was to investigate the effect of sun glare on pedestrian fatalities.

Design A population-based case–control study.

Setting Taiwan.

Participants Using the Taiwan National Traffic Crash Data and sunrise and sunset data from the National Oceanic and Atmospheric Administration (NOAA) for the period 2003–2016, 100,411 pedestrians involved in crashes were identified. Of these crashes, 13,355 and 87,056 were glare-related (case) and non-glare-related (control) crashes, respectively.

Methods To account for unobserved heterogeneity, mixed logit models were estimated to identify the determinants of pedestrian fatalities.

Main outcome measures Pedestrian fatalities.

Results Pedestrians involved in glare-related crashes were more likely to be fatally injured than those in non-glare-related crashes ($\beta = 0.527$; $t = 3.21$). Other contributory factors to fatal injuries among pedestrians were older pedestrians (β = 0.553; *t* = 2.33), male drivers (β = 0.324; *t* = 2.33), older drivers (β = 0.218; *t* = 2.14), intoxicated motorists (β = 0.606; *t* = 2.85), rural roadways (β = 0.985; *t* = 3.92), overtaking manoeuvres (β = 0.472; *t* = 3.58), heavy vehicle crash partners (β = 0.248; *t* = 2.78), and sunset hours (β = 0.274; *t* = 3.08). Walking against traffic appeared beneficial for decreasing injury severity (β = −0.304; *t* = −2.76).

Conclusions Sun glare is associated with pedestrian fatalities. Older pedestrians, male drivers, older drivers, and intoxicated motorists are prevalent determinants of pedestrian fatalities in glare-related crashes.

Keywords: Sun glare; Pedestrian fatalities; Crashes; Injury

Strengths and limitations of this study

- This is the first nationwide population-based case–control study of the associations between pedestrian fatalities and sun glare.
- Glare-related crashes were defined by adjusting vehicle travel direction and orientations of sunrise and sunset.
- Glare-related crashes were defined when the angular distance between the driver’s line of sight and the sun was between 0° and 45°.
- Limitations of this study include data, such as geographic characteristics,

unavailable in the two datasets.

INTRODUCTION

Driving is a highly visual task that involves visual function and processing for establishing effective control over a vehicle.[1] Research[2 3] has suggested that bright sunlight is ideal for driving because it increases the contrast, resolution, and luminosity of the surrounding landscape. As a result, however, drivers may misinterpret the speed at which parts of the surrounding landscape are approaching and underestimate their velocity, prompting them to compensate by accelerating.[4 5]

Generally, bright sunlight causes temporary blindness when the sun is at a relatively low altitude (i.e., just after sunrise or before sunset when the sun is just above the horizon) and its rays fall directly in an individual's line of sight. Using a simulator, Gray and Regan[6] assessed driving performance in both the absence and presence of a low sun. They reported that sun glare resulted in a significant reduction in the safety margin accepted by drivers, the mean number of crashes was significantly higher during conditions of glare than those without glare, and older drivers exhibited significantly greater reductions in the safety margin than did younger drivers. Another simulation study was conducted by Theeuwes et al.,[7] who reported that low glare resulted in their participants (drivers) exhibiting a significant decrease in the ability to detect simulated pedestrians along the roadside. Theeuwes et al.[7] also revealed that older participants reduced their driving speed the most and exhibited the largest decrease in successful pedestrian detection.

Churchill et al.[8] employed a geometric model to examine whether sun glare affects the speeds of drivers on roadways and concluded that changes in speed as a result of sun glare affected highway congestion. Jurado-Piña and Pardillo Mayora,[9] in an investigation of the maximum tolerable sun glare determined that glare occurs when at specific angular distances between a driver's line of sight and the sun; these angular distances are 19° for a 40-year-old driver and 25° for a 60-year-old driver. Anue[10] suggested that sun glare typically does not occur at angular distances greater than 25°.

Several studies have investigated whether a direct relationship exists between sun glare and crashes by using data from police reports or hospitals. In a longitudinal study of patients who had been hospitalised because of a motor-vehicle crash, Redelmeier and Raza[11] concluded that bright sunlight was associated with an increased risk of life-threatening crashes in Canada. By analysing police-reported crash data from Arizona, Mitra and Washington[12] indicated that sun glare was a crucial overlooked variable that could explain intersection crashes and that including this variable improved the explanatory power of statistical models. By linking police-reported crash data from Arizona with sunrise and sunset data from the

National Oceanic Atmospheric Administration (NOAA), Mitra[3] concluded that the odds of glare causing a crash were higher on roadways running eastbound and westbound than those running northbound and southbound. Mitra[3] further indicated that rear-end and angle crashes at signalised intersections were affected by sun glare, but that the severity of motorist injury was unaffected by sun glare.

By analysing the traffic-crash database of Chiba, Japan, Hagita and Mori[13] revealed that crashes involving pedestrians or bicycles at intersections were more likely when the sun was below 45° above the horizon in the driving direction. Sun et al.,[14] analysed police-reported crash data in Edmonton, Alberta, Canada, reported similar findings, concluding that sun glare significantly contributed to crash occurrence, especially at intersections. Furthermore, they indicated that the effect of sun glare on crash occurrence during mornings on eastbound roads and evenings on westbound roads is significantly greater during the spring and autumn months and that certain crash types (e.g., crashes related to signal violation, failure to yield to pedestrians/cyclists, and improper turning and lane changing) are more likely during periods of sun glare. By analysing police-reported crash data, Choi and Singh[15] revealed that, when compared to other age groups, elderly motorists tend to have a greater propensity for striking other vehicles in conditions of sun glare, especially on roadways that are not physically divided.

According to our literature review, a significant gap remains in the understanding of the relationship between sun glare and pedestrian fatalities, conditional upon a pedestrian occurring. The primary research hypothesis of the present study was that pedestrian injury severity increases as visibility decreases (i.e., during sun glare). This study therefore investigated whether sun glare is associated with pedestrian fatalities. This study also examined the determinants of pedestrian fatalities in crashes related to sun glare.

MATERIALS AND METHODS

Data source

By using the Taiwan National Traffic Crash Dataset as well as sunrise and sunset data from the NOAA for the period from 2003 to 2016 (National Oceanic Earth System Research Laboratory and Atmospheric Administration,[16] accessed: 2018-08-22), the current study examined the effect of sun glare on pedestrian fatalities, given that a crash involving a vehicle and pedestrian has occurred. The Taiwan National Traffic Crash Dataset comprises two types of file: crash files and vehicle and victim files. Crash files contain general information on the times and dates of crashes, as well as weather, road conditions, lighting conditions, and road types. Vehicle and victim files contain vehicle-related information, such vehicle type, manoeuvres, first point of impact, and orientation, as well as driver and casualty information, such as age, sex, and injury severity. Injury severity is classified into one of two levels: fatality or injury. Victims who die within 24 h as a result of a crash are classified as fatalities, whereas victims who sustain injuries, whether mild or severe, are classified as cases of injury.

Daily sunrise and sunset times and orientation are available from the NOAA. The sunrise and sunset orientation data for Taiwan are presented in online supplementary Appendix 1. By using the data on the temporal characteristics (i.e., time and date) and orientation of vehicle crashes from the Taiwan National Traffic Crash Dataset, pedestrian crashes were matched with the sunrise and sunset data of the NOAA and subsequently classified into glare-related or non-glare-related crashes. The Institutional Review Board affiliated with Taipei Medical University approved our study (IRB#: N201808071). Personal identification data, such as name or identification number, are not available in the dataset.

A glare-related crash was defined as a crash in which the following two conditions were satisfied: the car was travelling in a direction towards the sunrise or sunset and the angular distance between the driver's line of sight and the sun was between 0° and 45°. Data on a vehicle's travel orientation (north, south, east, or west) are available from the National Traffic Crash Dataset, and data on sun orientation are available from the NOAA. The angular distances were adjusted according to the time of the crash (available from the National Traffic Crash Dataset) and daily sunrise and sunset times (available from the NOAA).

For example, according to the Taiwan National Traffic Crash Dataset, a car–pedestrian crash occurred in Hsinchu City, where a car heading northeast collided with a pedestrian at 06:18 on 18 June, 2016. Angular distances from 0° to 45° were reported[13] to cause sun glare and potentially affect traffic safety in Japan. We adopted these same angular distances as the threshold for defining a glare-related crash. According to the NOAA website, for this particular (18 June, 2016) and location (Hsinchu City with latitude of 24.778°N and longitude of 120.988°E), the sun rose from northeast, and the sunrise and sunset times were at 05:07 and 18:47, respectively. The daytime length for this particular day was 13 h and 40 min, equivalent to 820 min. The angular distances for sunrise and sunset are 0–180°, respectively; on this particular day, the sun moved 0.2195° every minute (180/820 = 0.2195). The adopted angular distance of 45° is equivalent to 205 min (45/0.2195 = 205); therefore, the glare times transformed from the angular distances of 0°–45° for this particular crash can be between 05:07 and 08:32 (range of 205 min). This particular crash was therefore classified as a glare–related crash because the car was headed northeast (which was the direction of the sunrise) and the time of the crash

(06:18) was associated with an angular distance within 0°–45° (i.e. times between 05:07 and 08:32).

A flow-chart of the sample selection from the Taiwan Traffic Crash Dataset for the period from 2003 to 2016 is presented in online supplementary Appendix 2. A total of 195,258 pedestrian casualties from traffic crashes during this period were selected from the dataset. In our sample, each pedestrian was counted. Only crashes involving a single pedestrian were considered in this study; crashes involving two or more pedestrians (accounting for 0.12% of all pedestrian crashes) were excluded. This study also considered only pedestrian crashes in which the crash partner was a motorcycle, car, taxi, or heavy vehicle (e.g. bus or coach). Crashes that occurred during adverse weather conditions, such as rain, fog, or clouds, were excluded (n = 45,712). A total of 917 cases had missing data with regard to date, time, or vehicle orientation. Because these cases (adverse weather conditions and missing data) were not mutually exclusive, the total number of cases excluded was 45,365, yielding a total of 149,839 valid cases of pedestrian casualties. These valid cases were matched with the NOAA sunrise and sunset data.

After crashes that had occurred after sunset or before sunrise (n = 49,428) were excluded, 100,411 cases of pedestrian casualties remained. Of the 100,411 pedestrians that were matched with the sunrise and sunset data from the NOAA, 13,355 were glare-related cases (treated as cases), and 87,056 were non-glare-related cases (treated as controls).

Definition of variables

The following demographic data were collected regarding the pedestrians in cases of casualties: sex, age (four groups: <18, 18–40, 41–64, and ≥65 years), alcohol use (yes: breathalyser test results of ≥0.15 mg/L or blood-alcohol concentration [BAC] level >0.03%; no: breathalyser test results <0.15 mg/L or BAC level ≤ 0.03%), licence status (licensed: with a valid licence; unlicensed: without a valid licence), and pedestrian crossing manner (facing traffic: pedestrians walking towards traffic; back to traffic: pedestrians walking with their backs to traffic; crossing: pedestrians crossing the street).

In Taiwan, those under the age of 18 are identified as teenagers who are unable to legally ride motorcycles or drive cars. Those aged 65 years or older were identified as elderly individuals. The remaining individuals aged 18–64 were classified into two even age intervals: 18–40 and 41–64 years. BAC data were obtained by police who conducted breathalyser tests or who ordered follow-up blood tests at hospitals. According to Taiwanese law, drivers with either breathalyser test ≥ 0.15 mg/L or BAC level > 0.03% are considered to be drink driving. Data from breathalyser tests or

BAC levels were available only for motorists and not for pedestrians because, by law, only motorists involved in crashes are required to be tested for alcohol consumption.

The vehicle attribute considered was the crash partner (motorcycle, car, taxi, or heavy vehicle, such as a bus or coach). The following road factors were considered: sun glare (yes: affected by sun glare; no: unaffected by sun glare) and crash location (rural: roadways with speed limits of ≥51km/h; urban: roadways with speed limits of ≤50km/h). Two temporal factors, the month of the crash (spring/summer: March–August; autumn/winter: September–February) and days of the crash (weekday: Monday–Friday; weekend: Saturday or Sunday), were examined.

Patient and public involvement

The current research analysed national police-reported crash data as well as sunrise and sunset data from the NOAA, which are anonymised datasets. Neither patients nor the public were involved in this study.

Statistical analysis

The distribution of pedestrian injury severity according to a set of variables (i.e. human attributes, environmental factors, and vehicle characteristics) is reported in this study. Chi-square tests were conducted to examine the association between the independent variables and pedestrian injury severity. Because the dependent variable was binary (fatality vs. injury), binary mixed logit models, which allow parameter coefficients to have distributions rather than be fixed across individuals, were estimated. The variables discovered through chi-squared testing to be associated with the outcome ($p < 0.2$) were then incorporated into multivariate mixed logit models. To detect multi-collinearity among the variables (all categorical), a chi-square independent test was conducted, and Cramer's V[17] was estimated. To determine whether sun glare was associated with pedestrian fatalities, one overall model that included sun glare as one of the variables was utilised. One additional model with interaction terms of sun glare with other variables was subsequently estimated.

Mixed logit models were estimated to account for unobserved heterogeneity that may have arisen because of unmeasured variables, such as risk perception, behavioural factors, and other socioeconomic factors not available in the police-reported crash data. One example of a behavioural factor is distraction by phone use that may result in risk-taking inclinations and consequently an increased risk of injury.[18 19] Ignoring the effects of unobserved variables may lead to inconsistent estimates in all statistical models.[20]

In the present study, the utility of the injury severity *i* for a crash *n* was defined as follows:

$$IS_{in} = \beta_n X_{in} + \varepsilon_{in} \qquad \text{Eq. (1)}$$

where IS_{in} is an injury-severity function determining the injury-severity category i (fatal or injury) for an individual pedestrian n; X_{in} is a vector of the observed variables, such as pedestrian and driver attributes, vehicle characteristics, and environmental or temporal variables, β_n is a vector of the parameters associated with X_{in}; and ε_{in} is the error term. The mixed logit model uses β_n as a vector of estimable parameters, which vary among pedestrians. The variation is observed with density $f(\beta/\theta)$, where θ is a vector of the parameters of the density distribution. In most applications, mixed models specify that the density f has a continuous distribution, such as a normal, lognormal, triangular, or uniform distribution.

Given error terms that are independent and identically Gumbel distributed[21], the unconditional probability of one alternative i (from the set of injury-severity categories I) is the integral of the conditional probability with a multinomial logit form over the parameter β of density f:

$$P_{in} = \left(\frac{\exp(\beta' X_{in})}{\sum_{J=1}^{I} 1 + \exp(\beta' X_{nj})} \right) f(\beta|\theta) d\beta \qquad \text{Eq. (2)}$$

All parameters are initially assumed to be random; then, their estimated standard deviations are evaluated using a zero-based (asymptotic) *t* test for each parameter. One study[20] pointed out that a simulation-based maximum likelihood with 200 Halton draws may provide a more efficient distribution of draws for numerical integration and requires fewer draws to achieve convergence. We attempted to increase the number of Halton draws, and the results appeared stable with the use of 1000 Halton draws.

RESULTS

Table 1 lists the distribution of pedestrian injury severity according to a set of variables. Of the 13,355 glare-related cases, 329 pedestrians (2.46%) sustained fatal injuries, which is higher than those in non-glare-related crashes (1.83%). Majority of pedestrian crashes involved motorists with valid licences (85.65%), sober motorists (85.97%), urban roadways (89.57%), pedestrians who were hit while crossing the street (65.85%), or non-glare conditions (86.70%) or occurred on weekdays (74.83%).

Table 1: Distribution of pedestrian injury severity according to a set of variables for the period 2003–2016.

		Fatality	Injury	χ^2 test
	N	n(%)	n(%)	p-value
Total	100411	1925(1.92)	98486(98.08)	
Sun glare				
Yes	13355(13.30)	329(2.46)	13026(97.54)	<0.01

	N	Fatality n(%)	Injury n(%)	χ^2 test p-value
No	87056(86.70)	1596(1.83)	85460(98.17)	
Pedestrian gender				
Male	50942(50.73)	1015(1.99)	49927(98.01)	0.08
Female	49469(49.27)	910(1.84)	48559(98.16)	
Driver gender				
Male	53351(53.13)	1132(2.12)	52219(97.88)	<0.01
Female	47060(46.87)	793(1.69)	46267(98.31)	
Pedestrian age (years)				
<18	3644(3.63)	67(1.84)	3577(98.16)	<0.01
18-40	25851(25.75)	154(0.60)	25697(99.40)	
41-64	31283(31.15)	352(1.13)	30931(98.87)	
≥65	39633(39.47)	1352(3.41)	38281(96.59)	
Driver age (years)				
<18	4458(4.44)	103(2.31)	4355(97.69)	<0.01
18-40	25808(25.70)	295(1.14)	25513(98.86)	
41-64	32523(32.39)	474(1.46)	32049(98.54)	
≥65	37622(37.47)	1033(2.75)	36589(97.25)	
Driver licence				
Licensed	86007(85.65)	1609(1.87)	84398(98.13)	0.01
Unlicensed	14404(14.35)	316(2.19)	14088(97.81)	
Alcohol use for driver				
No	86322(85.97)	1512(1.75)	84810(98.25)	<0.01
Yes	14089(14.03)	413(2.93)	13676(97.07)	
Seasons				
Spring/summer	47671(47.48)	914(1.92)	46757(98.08)	0.99
Autumn/winter	52740(52.52)	1011(1.92)	51729(98.08)	
Crash location				
Rural	10475(10.43)	352(3.36)	10123(96.64)	<0.01
Urban	89936(89.57)	1573(1.75)	88363(98.25)	
Crash partner				
Motorcycle	33221(33.09)	643(1.94)	32578(98.06)	<0.01
Car	45963(45.77)	801(1.74)	45162(98.26)	
Taxi	9655(9.62)	208(2.15)	9447(97.85)	
Heavy vehicle	11572(11.52)	356(3.08)	11216(96.92)	
Pedestrian movement				
Facing traffic	9704(9.66)	172(1.77)	9532(98.23)	<0.01

	N	Fatality n(%)	Injury n(%)	χ^2 test p-value
Back to traffic	24584(24.48)	623(2.53)	23961(97.47)	
Crossing	66123(65.85)	1130(1.71)	64993(98.29)	
Car manoeuvre				
Straight	50836(50.63)	862(1.70)	49974(98.30)	<0.01
Changing lane	15625(15.56)	257(1.64)	15368(98.36)	
Overtaking	21339(21.25)	601(2.82)	20738(97.18)	
Turning	12611(12.56)	205(1.63)	12406(98.37)	
Sunset				
Sunset	8325(8.29)	214(2.57)	8109(97.41)	<0.01
Other times	87056(86.70)	1596(1.83)	85460(98.17)	
Sunrise	5030(5.01)	115(2.29)	4915(97.71)	
Weekdays				
Weekday	70366(70.08)	1267(1.80)	69099(98.20)	<0.01
Weekend	30045(29.92)	658(2.19)	29387(97.81)	

Through chi-square testing, the following variables were determined to be associated with the outcome: sun glare; pedestrian and driver sex and age; driver license possession and alcohol consumption; crash month, location, and partner; pedestrian movement; car manoeuvre; sunset hours; and day of the week. These factors were then incorporated into the mixed logit models.

Table 2 presents the estimation results of the mixed logit model of pedestrian injury severity. We compared the Akaike Information Criterion (AIC) of the models when determining the optimal distribution and determining whether parameters were fixed or random; male motorists and heavy vehicles as crash partners were determined to be random parameters, with a uniform distribution that appears to provide the best statistical fit.

Table 2: Mixed logit model estimation results for pedestrian injury severity during the period 2003–2016 [a] (n = 100,411).

Variable	Parameter	Standard error	*t*-value
Fatal injury			
Fixed parameters			
Constant	−0.531	0.215	−2.47
Glare-related crash	0.527	0.164	3.21
Pedestrian facing traffic	−0.304	0.110	−2.76
Pedestrian aged 65+ years	0.553	0.237	2.33
Motorist aged 65+ years	0.218	0.102	2.14
Rural roadway	0.985	0.251	3.92
Intoxicated motorist	0.606	0.213	2.85
Weekend	0.134	0.053	2.53
Overtaking manoeuvre	0.472	0.132	3.58
Sunset	0.162	0.074	2.19
Random parameters			
Male motorist	0.324	0.139	2.33
Standard deviation of distribution	0.389	0.163	2.39
Heavy vehicle partner	0.274	0.110	2.49
Standard deviation of distribution	0.622	0.290	2.14

Restricted log-likelihood (constant only): −8,267.1

Log-likelihood at convergence: −5,806.4

ρ^2= 0.298

[a] The outcome 'injury' is the baseline case with its parameters set at zero.

According to the results listed in Table 2, glare-related crashes contributed to fatalities (t = 3.21), and the estimated parameter was fixed across all observed pedestrians (the AIC, when fixed, was smaller than when allowed to be random). The parameter implies that glared-related crash was more likely to result in fatal injuries among pedestrians than a non-glare–related crash. Other factors discovered to have fixed effects on observed pedestrians and increase the likelihood of fatal injuries were pedestrians aged 65 years or older, motorists aged 65 years or older, rural roadways, intoxicated motorists, weekend days, overtaking manoeuvres, and sunset hours.

The parameter for the parameter of male motorist appeared to be random, having a normal distribution with a mean of 0.324 and standard deviation of 0.389 (see Table 2), indicating that individual pedestrians being struck by male motorists had different parameters. Given the estimates (mean = 0.324, standard deviation = 0.389), approximately 79.8% of pedestrians had a higher probability of sustaining fatal injuries when all other variables remained constant. Another parameter found to have a random effect across the sample of pedestrians was the variable of a heavy vehicle as the crash partner (with a normal distribution). This parameter had a mean of 0.274 and standard deviation of 0.622 (see Table 2), indicating that individual pedestrians struck by heavy vehicles have different parameters, with 67.0% of the distributions resulting in a positive parameter (increasing the likelihood of fatal injuries) and 33.0% resulting in negative parameter (decreasing the likelihood of fatal injuries).

The direction of travel of pedestrians relative to vehicular traffic was also discovered to affect pedestrian fatalities (t = −2.76). This fixed parameter suggests that pedestrians who faced traffic while walking were less likely to sustain fatal injuries than were those making other movements, such as walking with their backs to traffic or crossing the street.

Table 3 presents the estimation results of the mixed logit model of pedestrian injury severity specifically in glare-related crashes. For this model, the only random parameter (with a uniform distribution) was the variable of a heavy vehicle as the crash partner. The heterogeneous effect indicates that crashes involving heavy vehicles were associated with both higher and lower likelihoods of pedestrians sustaining fatal injuries. We speculate that this heterogeneous effect is caused by variance in the experience level among certain driver groups, with more experienced drivers exhibiting a decreased likelihood of causing fatal injuries. In other words, heavy vehicles are normally operated by professional drivers, with the majority of drivers in this group being men and middle-aged or older individuals. The heterogeneity of the heavy vehicle partner variable presented supporting estimating a mixed logit model of pedestrian injury severity because such effects are difficult to identify when using a logit framework with numerous interaction terms.

Table 3: Mixed logit estimation results for pedestrian injury severity with interaction terms of glare-related crashes and other variables [a] (n = 100,411)

Variable	Parameter	Standard error	*t*-value
Fatal injury			
Fixed parameters			
Constant	−0.324	0.139	−2.33
Male motorist	0.193	0.069	2.80
Sunset	0.274	0.089	3.08
Pedestrian facing traffic × glare crash	−0.439	0.126	−3.48
Pedestrians aged 65+ years	0.533	0.210	2.54
Motorists aged 65+ years × glare crash	0.432	0.143	3.02

Rural roadways × glare crash	0.684	0.190	3.60
Intoxicated motorist	0.461	0.154	2.99
Weekend	0.157	0.075	2.09
Overtaking manoeuvre	0.329	0.121	2.72
Random parameter			
Heavy vehicle as crash partner	0.248	0.089	2.78
Standard deviation of distribution	0.526	0.211	2.49
Restricted log-likelihood (constant only): −7,302.7			
Log-likelihood at convergence: −5,054.6			
ρ^2=0.308			

[a] The outcome ‘injury‘ constituted the baseline, with its parameters set at zero

This mixed logit model with interaction terms of glare crashes with other variables highlights several crucial features of glare crashes. For example, several interaction terms were discovered to affect fatalities and fixed across the observed pedestrians: facing traffic × glare crash, elderly motorist × glare crash, and rural roadway × glare crash. It appears that facing traffic in a glare-related crash is a protective factor against pedestrian fatalities. Injuries to pedestrians were more likely to be fatal in glare crashes in which the drivers were elderly. Furthermore, in glare crashes that took place in a rural setting, injuries were more likely to be fatal than otherwise.

DISCUSSIONS

By using the National Traffic Crash Dataset and sunrise and sunset data from the NOAA, the present study examined whether sun glare was associated with pedestrian fatalities involved in motor vehicle crashes. This research contributes to the growing literature on pedestrian safety as well as fills a major research gap regarding the effect of sun glare on pedestrian fatalities. Regarding methodological contributions, the proposed models offer methodological flexibility to identify individual-specific heterogeneity that may arise as a result of other unmeasured factors related to motorist experience or behaviour or geographic characteristics. When developing intervention strategies for improving pedestrian safety in sun-glare conditions, the heterogeneous effects of certain variables (which cannot be determined with traditional logit models) should be considered.

The empirical contributions of this research are those findings related to the factors affecting pedestrian fatalities. The identification of these risk factors may provide policy-makers with information crucial to establishing suitable policies and strategies that may reduce the risk of crashes or severity. The following findings merit further discussion.

Most drivers commute during hours of extreme sun glare. It is therefore not surprising that more crashes occur on roadways that experience a significant portion of traffic during peak morning (sunrise) and afternoon (sunset) hours. The adverse effect of sun glare on crash occurrence has been well documented in relevant literature.[3 14] However, Mitra[3] discovered that motorist injury severity was not increased in glare conditions, possibly as a consequence of reduced travel speed.[8] Such a protective effect of sun glare against associated motorist injury severity does not apply to pedestrians; our study concludes that glare conditions (as indicated in the overall model) are associated with pedestrian fatalities.

In our study, the adverse effect of sun glare was greater on rural roadways where crashes occur at higher speeds and motorists may not expect to encounter pedestrians as often as they would on urban roadways. One commonly-adopted engineering measure is the use of adjust message signs to warn drivers of the risk of sun glare at times and locations (i.e. rural roadways) prone to sun glare.[9]

Mitra[3] noted that the odds of glare causing crashes at intersections were higher during the morning hours and in autumn and winter months in Arizona, United States. In our study, seasons had a negligible effect on pedestrian fatalities. Adding to the research conducted by Hagita and Mori, [22] who concluded that the rate of pedestrian crashes shortly after sunset was higher than that at any other time in Japan, our study revealed that compared with sunrise, the adverse effect of sun glare on pedestrian fatalities was greater during sunset in Taiwan. Therefore, sun glare during sunset hours may not only increase pedestrian crashes, as indicated by Hagita and Mori[22], but also affect the resulting injury severity. Evening commutes are often risky due to fatigue, distraction, or other factors unrelated to sun glare. In our study, injuries sustained by pedestrians were more likely to be fatal at sunset than any other daytime of day. Additional research is warranted to examine whether sun glare affects pedestrian fatalities in evening commuting crashes.

Studies have suggested that compared to sober motorists, intoxicated motorists are more likely to leave pedestrians unattended by leaving the crash scene, thereby increasing pedestrian injury severity. Furthermore, alcohol use has been discovered to lead to hit-and-runs at night and during the weekend.[23 24] Our study revealed that the combined effects of alcohol consumption and sun glare were associated with pedestrian fatalities. Similar to other studies,[23 24] our research highlights, in particular, the effect of motorist alcohol consumption on the likelihood of fatality and on the weekends.

Studies have consistently reported that elderly motorists are the group most affected by sun glare. For example, two simulation studies conducted by Gray and Regan[6] and Theeuwes et al.[7] reported that in conditions of sun glare, older drivers executing a turning manoeuvre demonstrated significantly greater reductions in safety margin than did younger drivers, and older drivers demonstrated the most significant decrease in the ability to successfully detect pedestrians. Studies analysing real-life police-reported crash data[15] have indicated that in conditions of sun glare, older drivers are more likely to strike other vehicles. Our study contributes to the literature on pedestrian safety by concluding that older motorists, when affected by sun glare, are likely to cause fatal injuries to pedestrians when crashes occur. Advance-warning signs or educational efforts to increase older drivers' awareness of sun-glare conditions may reduce the likelihood of vehicle crashes or pedestrian injury severity.

In our study, no discrepancy was found between injuries in spring/summer and autumn/winter. We speculate that this is primarily because the anticipated effect of sun glare in different seasons may be offset by, for example, typhoons that strike Taiwan in summer and northeast monsoon in winter. Our result differs from those from large country,[3] where the adverse effect of sun glare was found to be greater in autumn and winter months. Such studies have been conducted in large countries such as the United States, where the climate changes substantially across latitudes, whereas Taiwan is a small island where climate changes little throughout the country.

Considerable work has concluded that older pedestrians are more likely to be fatally or severely injured in crashes, both during daytime and night conditions.[25] Our research provides ample evidence to suggest that injuries sustained by older pedestrians in crashes caused by sun glare are more likely to be fatal than those sustained by younger pedestrians. Whether the reduced conspicuity of pedestrians (particularly older pedestrians) under conditions of sun glare (twilight) plays a role in this effect is uncertain. However, enhancing the conspicuity of pedestrians with the use of visibility aids, not only in night conditions[26] but also in twilight conditions, may be beneficial for reducing crash risk or severity.

Adding to the research conducted by Sun et al.,[14] who reported that crashes related to improper turning or lane changing were more likely to occur during periods of sun glare, the present study reveals an association between the execution of overtaking manoeuvres during periods of sun glare and pedestrian fatalities. Injuries sustained in crashes caused by vehicles executing overtaking manoeuvres are commonly severe because motorists must accelerate to overtake other vehicles. In Taiwan, it is common for motorists to execute overtaking manoeuvres by using roadway shoulders, where pedestrians walk. Motorists should be aware of the risk they pose to pedestrians when overtaking other vehicles, particularly during periods of sun glare.

Studies have reported that facing traffic is beneficial for preventing pedestrian crashes[27] and reducing the severity of related injuries.[25] Our study complements these studies by concluding that walking against traffic is associated with decreased injury severity. In these cases, pedestrians' forward views may be well lit and thus be more favourable for pedestrians than walking in other directions. Expressing the necessity of facing traffic while walking along a street, particularly in conditions of sun glare, should be supplemented with information regarding the related safety benefits.

Although it varied among the study pedestrians, being struck by heavy vehicles increased the likelihood of fatal injuries. Although this finding agrees with those of other studies,[28 29] we additionally concluded that the effect of heavy vehicles was greater in conditions of sun glare. Notably, drivers of heavy vehicles tend to be professional. It is unclear whether driving this particular group of vehicles, in combination with undertaking longer hours of travel compared with those undertaken by a car driver, makes such drivers more susceptible to problems related to sun glare than other drivers are. Educational efforts can be directed towards drivers of heavy vehicles regarding driver susceptibility to sun glare, particularly on roadways with pedestrians.

This study had the following research limitations. First, it did not consider the surrounding topography; motorists travelling through areas with buildings or mountains, may be less susceptible to sun glare because the sun is occluded. By analysing geographic and police report data, likely times and locations for sun glare can be predicted, and motorists can be well informed regarding where and when to expect sun glare. Furthermore, we classified crashes as being related to glare when the angular distance between the driver's line of sight and the sun was between 0° and 45°, a threshold based on research in Japan.[13] Further research adopting more stringent thresholds of 10°, 20°, or 30° degrees or analysing the changes in this effect for motorists of different ages may attempt to compare their results with ours, as

473 indicated by Jurado-Piña and Pardillo Mayora.[9]

474 Due to limited funding, we could link only the National Traffic Crash Dataset and
475 NOAA data but not prehospital triage system or hospital data (e.g. the National
476 Health Insurance Research Dataset: NHIRD). We recommend that future research
477 link our data to clinical datasets that provide details on injuries (e.g. injured body
478 regions, hospitalisation) other than the condition of fatalities examined in this study.

479 Sun glare is a combined spatiotemporal factor. To broaden our collective
480 understanding of factors of pedestrian safety, collecting spatial and temporal data
481 whenever possible is paramount. The empirical results obtained in this study may be
482 unique to Taiwan because of its unique sunrise and sunset times and orientations. As a
483 result, until additional analyses are conducted using data from other countries to
484 determine whether sun glare is a salient factor of pedestrian fatalities, caution should
485 be exercised in generalising our findings for application in other settings.

486

487 **Contributors:** HPM drafted and revised the manuscript and established the
488 theoretical support for data analyses. PLC re-analysed the data and interpreted the
489 results. SKC reviewed relevant literature and analysed the data. LHC analysed the
490 data. VL edited the manuscript and reviewed relevant literature. CWP was responsible
491 for study design, contributed to the analysing and interpretation of data, drafted the
492 manuscript, and strengthened discussion and conclusion. The final version of the

manuscript was read and approved by all contributing authors.

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Data sharing statement: Only citizens of Taiwan who fulfil the requirements of conducting research projects are eligible to apply to use the dataset. The use of dataset is limited to research purposes only. The authors had no special access privileges that others would not have.

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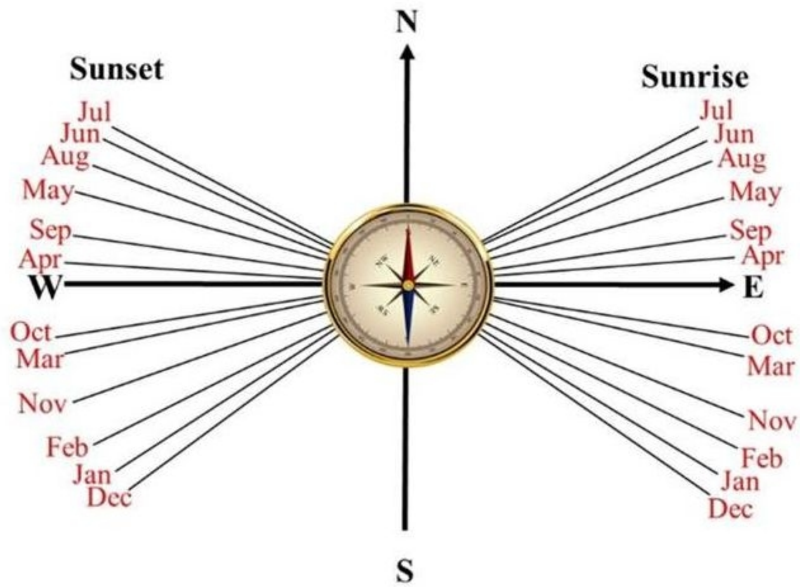
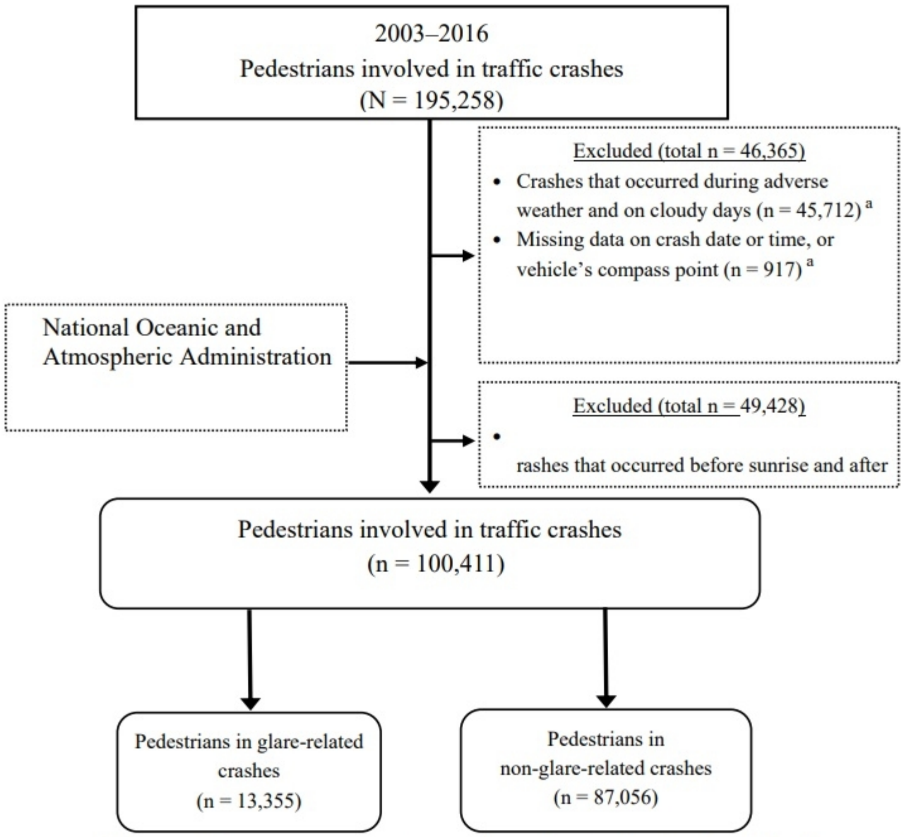
Appendix 1: Directions of sunrise and sunset in Taiwan



66x49mm (300 x 300 DPI)

Appendix 2: Study flow chart



[a] Because these cases were not mutually exclusive, the total number of cases excluded was 45,365.

209x204mm (96 x 96 DPI)

STROBE Statement

Checklist of items that should be included in reports of ***case-control studies***

Section/Topic	Item No	Recommendation	Reported on Page No
Title and abstract	1	(*a*) Indicate the study's design with a commonly used term in the title or the abstract	1
		(*b*) Provide in the abstract an informative and balanced summary of what was done and what was found	2–3
Introduction			
Background/rationale	2	Explain the scientific background and rationale for the investigation being reported	4–6
Objectives	3	State specific objectives, including any prespecified hypotheses	7
Methods			
Study design	4	Present key elements of study design early in the paper	8–10
Setting	5	Describe the setting, locations, and relevant dates, including periods of recruitment, exposure, follow-up, and data collection	8–12
Participants	6	(*a*) *Cohort study*—Give the eligibility criteria, and the sources and methods of selection of participants. Describe methods of follow-up *Case-control study*—Give the eligibility criteria, and the sources and methods of case ascertainment and control selection. Give the rationale for the choice of cases and controls *Cross-sectional study*—Give the eligibility criteria, and the sources and methods of selection of participants	7–9
		(*b*) *Cohort study*—For matched studies, give matching criteria and number of exposed and unexposed *Case-control study*—For matched studies, give matching criteria and the number of controls per case	
Variables	7	Clearly define all outcomes, exposures, predictors, potential confounders, and effect modifiers. Give diagnostic criteria, if applicable	11,12
Data sources/measurement	8*	For each variable of interest, give sources of data and details of methods of assessment (measurement). Describe comparability of assessment methods if there is more than one group	11,12
Bias	9	Describe any efforts to address potential sources of bias	9
Study size	10	Explain how the study size was arrived at	10
Quantitative variables	11	Explain how quantitative variables were handled in the analyses. If applicable, describe which groupings were chosen and why	11,12
Statistical methods	12	(*a*) Describe all statistical methods, including those used to control for confounding	12–15
		(*b*) Describe any methods used to examine subgroups and interactions	12–15
		(*c*) Explain how missing data were addressed	12–15
		(*d*) *Cohort study*—If applicable, explain how loss to follow-up was addressed *Case-control study*—If applicable, explain how matching of cases and controls was addressed *Cross-sectional study*—If applicable, describe analytical methods taking account of sampling strategy	12–15
		(*e*) Describe any sensitivity analyses	N/A

Section/Topic	Item No	Recommendation	Reported on Page No
Results			
Participants	13*	(a) Report numbers of individuals at each stage of study—eg numbers potentially eligible, examined for eligibility, confirmed eligible, included in the study, completing follow-up, and analysed	10
		(b) Give reasons for non-participation at each stage	10
		(c) Consider use of a flow diagram	Appendix 2
Descriptive data	14*	(a) Give characteristics of study participants (eg demographic, clinical, social) and information on exposures and potential confounders	10
		(b) Indicate number of participants with missing data for each variable of interest	10
		(c) *Cohort study*—Summarise follow-up time (eg, average and total amount)	N/A
Outcome data	15*	*Cohort study*—Report numbers of outcome events or summary measures over time	N/A
		Case-control study—Report numbers in each exposure category, or summary measures of exposure	N/A
		Cross-sectional study—Report numbers of outcome events or summary measures	15
Main results	16	(*a*) Give unadjusted estimates and, if applicable, confounder-adjusted estimates and their precision (eg, 95% confidence interval). Make clear which confounders were adjusted for and why they were included	15–21
		(*b*) Report category boundaries when continuous variables were categorized	N/A
		(*c*) If relevant, consider translating estimates of relative risk into absolute risk for a meaningful time period	N/A
Other analyses	17	Report other analyses done—eg analyses of subgroups and interactions, and sensitivity analyses	N/A
Discussion			
Key results	18	Summarise key results with reference to study objectives	22–29
Limitations	19	Discuss limitations of the study, taking into account sources of potential bias or imprecision. Discuss both direction and magnitude of any potential bias	27–29
Interpretation	20	Give a cautious overall interpretation of results considering objectives, limitations, multiplicity of analyses, results from similar studies, and other relevant evidence	27–29
Generalisability	21	Discuss the generalisability (external validity) of the study results	28–29
Other Information			
Funding	22	Give the source of funding and the role of the funders for the present study and, if applicable, for the original study on which the present article is based	29

**Give information separately for cases and controls in case-control studies and, if applicable, for exposed and unexposed groups in cohort and cross-sectional studies.*

Note: An Explanation and Elaboration article discusses each checklist item and gives methodological background and published examples of transparent reporting. The STROBE checklist is best used in conjunction with this article (freely available on the Web sites of PLoS Medicine at http://www.plosmedicine.org/, Annals of Internal Medicine at http://www.annals.org/, and Epidemiology at http://www.epidem.com/). Information on the STROBE Initiative is available at www.strobe-statement.org.