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# Evaluation of motorcycle safety strategies using the severity of injuries

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ABSTRACT

The growth of motorcycle fatalities in California has been especially prominent, specifically with regard to the 24 and under age group and those aged 45–54. This research quantitatively examined factors associated with motorcyclist fatalities and assessed strategies that could improve motorcyclist safety, specifically focusing on the two age groups mentioned above. Severity of injury was estimated separately for both age groups with multinomial logit models and pseudo-elasticity using motorcycle-related collision data that was collected between 2005 and 2009. The results were compared with motorcyclists aged 35–44, a group that shows a consistent trend of fatalities.

This research found that lack or improper use of helmets, victim ejection, alcohol/drug effects, collisions (head-on, broadside, hit-object), and truck involvement were more likely to result in fatal injuries regardless of age group. Weekend and non-peak hour activity was found to have a strong effect in both the younger and older age groups. Two factors, movement of running off the road preceding a collision and multi-vehicle involvement, were found to be statistically significant factors in increasing older motorcyclist fatalities. Use of street lights in the dark was found to decrease the probability of severe injury for older motorcyclists. Driver type of victim, at-fault driver, local road, and speed violation were significant factors in increasing the fatalities of younger motorcyclists. Road conditions and collision location factors were not found to be statistically significant to motorcyclist fatalities.

Based on the statistically significant factors identified in this research, the following safety strategies appear to be effective methods of reducing motorcyclist fatalities: public education of alcohol use, promoting helmet use, enforcing heavy vehicle and speed violations, improving roadway facilities, clearer roadway guidance and street lighting systems, and motorcyclist training.



## 1. Introduction

United States fatalities involving motorcycle crashes have increased from a long-term perspective since 1997. According to Fatality Analysis Reporting System (FARS) data from 1997 to 2007, the average yearly fatality rate involving motorcycle crashes was 32 per 100 million vehicle miles traveled (VMT); this is considerably higher than fatality rates involving any other type of vehicle (FARS, 2012). California was the leading contributor to U.S. motorcyclist fatalities from 1997 to 2007 (NCAC, 2010). Additionally, since 1995 the yearly number of California (CA) motorist fatalities involving motorcycle crashes has been greater than the national rate (FARS, 2012).

Motorcycle safety improvements have been one of the most important issues in California's Strategic Highway Safety Plan (SHSP) (Kempton et al., 2006). Hence, in 2006, the SHSP established a specific safety goal of reducing the level of fatalities by 10 percent from 2004 to 2010. California intended to reduce motorcyclist fatalities by employing strategies related to the following action items (Kempton et al., 2006): educate the public on motorcycle safety; improve motorcycle training; improve the testing and licensing of motorcyclists; enhance the enforcement of motorcyclist violations and violations by the operators of other vehicles; improve motorcyclist visibility to other roadway users; improve roadway design to enhance motorcycle safety; and promote the use of helmets that meet USDOT standards. For each action item, SHSP also discussed key implementation issues including roadway

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surface changes, enforcement of existing helmet integrity laws, and training for older motorcyclists. Some safety strategies, such as enforcement and engineering, have the potential to make an immediate impact on reducing crashes, while the effects of educating riders to wear helmets may not be visible until years later. Despite the action items, California motorcyclist fatalities have increased by 60 percent from 2004 to the end of 2009 (SWITRS, 1995–2009), suggesting that the goal of reducing motorcyclist fatalities has not been achieved.

During the last 10 years a limited number of studies have attempted to explain the undesirable shift in motorcycle-related crashes and injuries in California. A technical study summarized roadway and rider contributing factors in California motorcycle crashes, but no statistical or quantitative methods were applied to identify the contributing factors (NCAC, 2010). A different study considered only helmet use and risk compensation in motorcycle crashes that occurred in Los Angeles (Ouellet, 2011). Therefore, there is an imperative need to assess the factors affecting the levels of motorcyclist severities in California - especially fatalities.

Based on Statewide Integrated Traffic Records System (SWITRS) data from 1999 to 2004, one of the most conspicuous trends is the number of motorcyclist fatalities and the age groups in which they occurred. The 45- to 54-year-old group had the largest percentage increase in fatalities, while the 35–44 age group had the highest number of fatalities. Since 2005, however, the age group data has shown a different trend. Even though the number of fatally injured motorcyclists aged 25–34 was greatest from 2005 to 2009, the increase in fatalities for this age group was still less than the rates of the other age groups during the same period. Motorcyclists aged 45–54 still had a larger percentage increase in fatalities than any other age group, and riders aged 24-years and younger had the second largest increase in fatalities. The 35–44 year old age group, however, remained relatively consistent with regard to its number of fatalities.

As a preliminary step, this study examined the effects of contributing factors on injury levels of motorcyclist victims aged 24 years old and younger, and those aged 45–54, targeting the fatal injury level. The study also compared the risk factors of these two groups to the risk factors and injury levels of motorcyclist victims aged 35–44.

## 2. Literature review

The literature review focuses on the effects of motorcyclist age and other related factors on injury severities. The majority of studies focus on younger and/or older age groups. Schneider and Savolainen examined the effects of factors associated with motorcyclist injury severities for single-vehicle and multi-vehicle crashes occurring at both intersection and non-intersection locations in Ohio (Schneider IV and Savolainen, 2011). In their study, age was initially examined as a series of indicator variables. Both younger and older drivers were found to be more prone to severe injuries. That is, motorcyclist age was found to have a significant impact on a 1% increase in age resulting in a 1.1% increase in fatalities involved in single-vehicle crashes. The age effects on incapacitating and fatal injuries were also evident in multi-vehicle crashes.

Geedipally et al. identified differences in factor impacts on injury severities of motorcycle crashes that occurred in urban and rural areas of Texas (Geedipally et al., 2011). The research showed that human and roadway-related factors such as age, alcohol, gender, lighting, and horizontal and vertical curves were significant factors in both urban and rural motorcycle crashes. Riders younger than 25 years of age were less likely to be involved in a fatality in either area, whereas riders older than 55 years of age were more likely to be involved in a rural fatality. The absence of street lights and the presence of higher speed limits in rural areas were identified as contributors to the increased probability of crashes for the older group.

Pai et al. examined three characteristics of automobile–motorcycle gap-acceptance accidents, including approach-turn, angle crossing, and angle merging crashes occurring at T-intersections to investigate the contributory factors to violations of the right-of-way traffic guideline. Based on a 15-year British Stats accident injury database, mixed logit models were estimated and an indicator for a rider aged 60 or above was found to be significant throughout all observations with a fixed effect on increasing the approach turn crashes (Pai et al., 2009). Similarly, Savolainen and Mannering used nested logit models to show how increasing a motorcyclists' age resulted in a much higher likelihood of an incapacitating injury when involved in single-vehicle and multi-vehicle crashes (Savolainen and Mannering, 2007a,b).

Other studies compared a driver's age, characteristics and behavior to motorcycle crashes and motorcyclist injury severities. In these studies young riders were found to be overrepresented in crashes due to lack of experience and higher level of engagement in high-risk activities such as illegal alcohol use, speeding, and not wearing or incorrectly wearing a helmet (Rome and Senserrick, 2011; Haque et al., 2009; Chang and Yeh, 2007; Mullin et al., 2000). On the other hand, contradictory results reported that age did not significantly affect the probability of motorcyclist injury severity. Zambon and Hasselberg used data from riders aged 16–30 to measure correlations between the individual, environment, vehicle and crash factors, and injury severity. Although age was found to increase the likelihood of injury risk, it was not associated with injury severity among young motorcycle drivers (Zambon and Hasselberg, 2007). In an Ohio study by Eustace et al., motorcyclists aged 25 years and older were found to have no statistically significant differences with regard to incapacitating and fatal injuries in multinomial probit model estimations (Eustace et al., 2011).

## 3. Methodology

Motorcyclist injury severities were recorded in five categories: fatal injury, severe injury, other visible injury, complaint of pain injury, and no injury. This kind of response data are well-suited for discrete multiple outcome models including ordered or unordered probability approaches (Schneider IV and Savolainen, 2011).

Even though motorcyclist injury severities have multiple discrete and ordered outcomes, the conventional ordered probability approach imposes a critical restriction of proportional odds; in other words, it is too arbitrary to assume that all coefficients of the ordered probability model are the same across all injury severities (Milton et al., 2008; Wang and Abdel-Aty, 2008). Moreover, underreporting associated with low-severity injuries can cause the ordered probability models to yield biased and inconsistent coefficient estimates (Savolainen and Mannering, 2007a,b).

Alternatively, a generalized version of the standard ordered logit and sequential logistic models were introduced to relax the restrictions of the proportional odds assumption in previous studies (Eluru et al., 2008; Jung et al., 2010). The generalized ordered response model is recommended only to confirm that the proportional odds assumption is valid, as the model is very anti-conservative (Peterson and Harrell, 1990). Additionally, the sequential logistic model would be less statistically efficient than fully informational methods because data at some stages of the binary response are removed.

Due to the critical limitations of using an ordered probability approach, an unordered probability approach (e.g. multinomial,

**Table 1**
Descriptive statistics of variables by age group, 2005–2009.

| Variable | | | Age groups | | |
|---|---|---|---|---|---|
| | | | Less than 25 | 35–44 | 45–54 |
| Response | Fatality | | 458 | 427 | 468 |
| | Severe injury | | 2031 | 1930 | 2022 |
| | Other visible injury | | 6962 | 4882 | 4695 |
| | Complaint of pain injury | | 3307 | 3365 | 3167 |
| | No injury | | 3092 | 2297 | 2201 |
| | Total | | 15850 | 12901 | 12553 |
| Explanatory | Victim type | Driver | 13813 | 12022 | 11544 |
| | | Passenger | 2037 | 879 | 1009 |
| | Victim sex | Female | 2066 | 1873 | 2011 |
| | | Male | 13784 | 11028 | 10542 |
| | Victim's use of helmet | Not used | 14167 | 11564 | 11333 |
| | | Used | 1683 | 1337 | 1220 |
| | Victim ejected | Ejected | 9219 | 7454 | 7171 |
| | | Others | 6631 | 5447 | 5382 |
| | Party type | At-fault | 10096 | 6812 | 6752 |
| | | Not-at fault | 5754 | 6089 | 5801 |
| | Alcohol/drug effect | Under effect | 939 | 1284 | 1344 |
| | | Not under effect | 14911 | 11617 | 11209 |
| | *Violation preceding collision* | Unsafe lane change/passing | 91 | 84 | 64 |
| | | Speed related violation | 995 | 770 | 636 |
| | | Improper Turning | 332 | 388 | 439 |
| | | Wrong side of road | 142 | 118 | 143 |
| | | Non-moving violation | 145 | 53 | 38 |
| | | Other violations | 330 | 186 | 157 |
| | *Movement preceding collision* | Stopping/slowing | 1034 | 1115 | 1252 |
| | | Turning | 1657 | 1155 | 1148 |
| | | Changing/merging lanes | 673 | 439 | 378 |
| | | Ran off road | 1040 | 964 | 1167 |
| | | Crossed into opposing lane | 265 | 159 | 202 |
| | | Passing other vehicle | 462 | 387 | 329 |
| | | Proceeding straight | 10088 | 8221 | 7644 |
| | | Other movements | 631 | 461 | 423 |
| | Weather at the time of collision | Rain/snow/fog/wind | 175 | 131 | 140 |
| | | Others | 15675 | 12770 | 12413 |
| | Collision season | Spring | 2841 | 2296 | 2242 |
| | | Summer | 4895 | 4028 | 3997 |
| | | Autumn | 3112 | 2885 | 2573 |
| | | Winter | 5002 | 3692 | 3741 |
| | Day of week at collision time | Weekday | 10671 | 8396 | 7587 |
| | | Weekend | 5179 | 4505 | 4966 |
| | Collision time | Nighttime | 795 | 675 | 346 |
| | | Peak hour | 5706 | 4899 | 4592 |
| | | Non-peak hour | 3038 | 7300 | 7435 |
| | *Road classification* | Local | 7100 | 5514 | 4773 |
| | | Interstate highway | 2294 | 2107 | 1773 |
| | | US highway | 468 | 535 | 471 |
| | | State route | 2371 | 2309 | 2753 |
| | | County road | 3599 | 2422 | 2777 |
| | Collision location | Intersection | 265 | 267 | 337 |
| | | Ramp/collector | 823 | 720 | 745 |
| | | Highway | 4732 | 4612 | 4607 |
| | | Not state highway | 10030 | 7302 | 6864 |
| | Number of parties | Multi-vehicle involved | 10577 | 8715 | 8036 |
| | | 1-vehicle involved | 5273 | 4186 | 4517 |
| | *Ramp intersection* | Ramp exit | 120 | 121 | 152 |
| | | Mid-ramp | 486 | 419 | 380 |
| | | Ramp entry | 61 | 50 | 56 |
| | | Ramp related within 100 ft | 156 | 130 | 157 |
| | | Intersection | 213 | 221 | 284 |
| | | Others | 52 | 46 | 53 |
| | Collision type | Head-on | 710 | 472 | 465 |
| | | Sideswipe | 2397 | 2232 | 1814 |
| | | Rear-end | 2904 | 2400 | 2396 |
| | | Broadside | 3459 | 2532 | 2329 |
| | | Hit object | 2282 | 1757 | 1634 |
| | | Overturned | 3296 | 2741 | 3174 |
| | | Others | 802 | 767 | 741 |
| | Road surface | Wet/snowy/icy/muddy/oily | 399 | 387 | 379 |
| | | Others | 15451 | 12514 | 12174 |
| | *Road condition* | Hole, deep ruts | 78 | 82 | 77 |
| | | Loose materials | 125 | 136 | 153 |
| | | Obstruction | 54 | 69 | 70 |
| | | Construction zone | 231 | 199 | 206 |
| | | Other unusual conditions | 149 | 117 | 144 |

Table 1 (*Continued*)

| Variable | | | Age groups | | |
|---|---|---|---|---|---|
| | | | Less than 25 | 35–44 | 45–54 |
| | Lighting | No unusual condition | 15213 | 12298 | 11903 |
| | | Dusk/dawn | 621 | 481 | 460 |
| | | Dark-street lighting | 2619 | 1837 | 1429 |
| | | Dark-no street lighting | 1005 | 815 | 764 |
| | | Daylight | 11584 | 9752 | 9885 |
| | Truck involved | Truck involved | 254 | 225 | 239 |
| | | Not truck involved | 15596 | 12676 | 12314 |

*Note.* Italics indicate that only the categories of a variable with the sample size greater than 30 are provided.

nested and mixed logit models) was conducted for a portion of this study. Numerous combinations and hierarchies for five levels of motorcyclist injury severities and model formulations were first examined using nested logit models. The statistical test implied that assuming independence of irrelevant alternatives (IIA) is sufficient when estimating each motorcyclist injury severity. Next, the unordered probability model, or multinomial logit model (MNL) was employed because it provides the advantage of consistent coefficient estimation despite underreporting and the possibility of estimating more flexible and various sets of factor effects on probabilities of multiple discrete outcomes (Geedipally et al., 2011). Note that the mixed logit approach has been less obvious in empirical applications, as biases in real data make it challenging to establish the distribution for a predefined functional form of random parameters (Algers et al., 1998). The MNL model was finally chosen to estimate factor influences on motorcyclist injury severities. The model is specified as:

$$V_{ij} = \beta_i X_{ij} + \varepsilon_{ij} \quad (1)$$

where, $V_{ij}$ is injury outcome $i$ for motorcyclist $j$; $\beta_i$ is the vector of coefficient estimates; $X_{ij}$ is the vector of parameters; and $\varepsilon_{ij}$ is an independently and identically distributed generalized extreme value error term.

The probability of a particular outcome in MNL model is as follows:

$$P_j(i) = \frac{\mathrm{EXP}(V_{ij})}{\sum_{j=1}^{J} \mathrm{EXP}(V_{ij})} \quad (2)$$

where $P_j(i)$ is the probability of the occurrence of injury severity $i$ out of all injury severity outcomes for motorcyclist $j$, and $J$ is total number of injury severities.

In the MNL model, the extent of the impact of certain variables on motorcyclist injury severity probabilities is defined by elasticity (Geedipally et al., 2011). The percent effect of a one percent change in the variable on the outcome probability of other severity types is referred to as cross-elasticity (Geedipally et al., 2011). For binary indicator variables, pseudo-elasticity of the probability is used because the use of standard elasticity gives misleading results (Shankar and Mannering, 1996):

$$E(X_{hi}) = \left[\frac{P_{ij}(X_{hi}=1)}{P_{ij}(X_{hi}=0)} - 1\right] \times 100 \quad (3)$$

where $E(X_{hi})$ is the pseudo-elasticity representing the percentage of change in the probability of that severity type $i$ when a binary variable $X_{hi}$ for motorcyclist $j$ is changed from 0 to 1.

## 4. Data

Data was utilized from SWITRS recorded by police in this study. SWITRS has collected data on each victim and party related in each collision that occurred in California since 1995. As mentioned in Section 1, the clearest trends of SWITRS data were the motorcyclist fatalities by age group, which are shown in Fig. 1. Note that the term “motorcyclist” in this study indicates motorcycle driver and passenger.

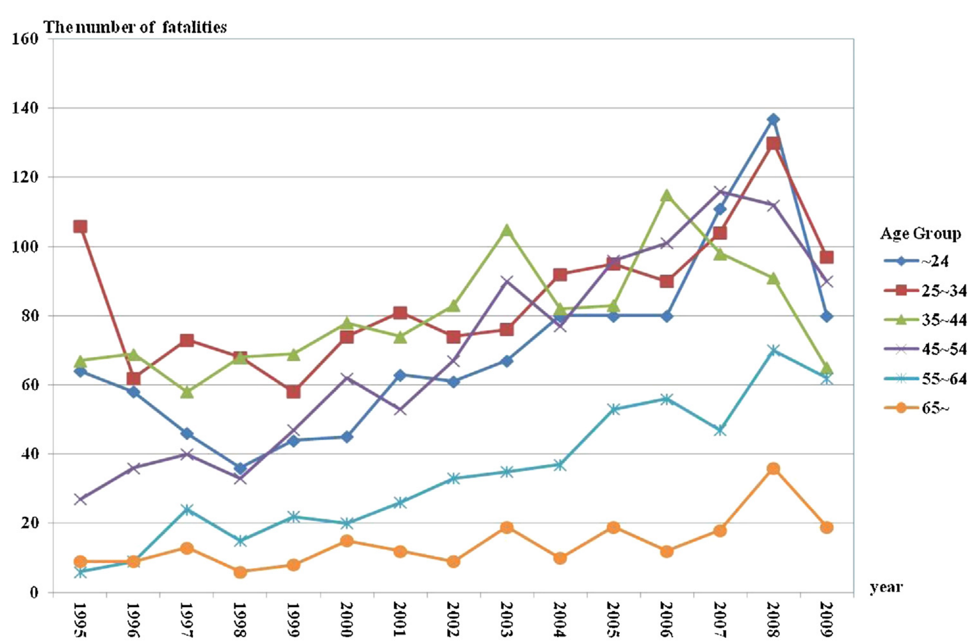


**Fig. 1.** The number of fatally injured motorcyclists by age group in California.

**Table 2**
Explanatory variables used in California study, 2005–2009.

| Data type | Indicator | | Description for indicator |
|---|---|---|---|
| Victim | Type | | Driver (1), Passenger (0) |
| | Sex | | Female (1), Male (0) |
| | Use of helmet | | Motorcyclist helmet not used (1), helmet used (0) |
| | Victim ejected | | Ejected (1), others (0) |
| Party | At-fault party | | At-fault in the collision (1), not at-fault (0) |
| | Driver's alcohol/drug effect | | Under alcohol/drug effect (1), not under effect (0) |
| | Violation preceding crash | Improper lane change/passing | Improper lane change or passing (1), others (0) |
| | | Speed related | Unsafe speed or following too closely (1), others (0) |
| | | Improper Turning | Improper or unsafe turning (1), others (0) |
| | | Wrong side of road | Wrong side of road (1), others (0) |
| | | Non-moving | Non-moving (1), others (0) |
| | | Other violations | Other violation (1), others (0) |
| | Movement preceding crash | Stopping/slowing | Stopped (1), others (0) |
| | | Turning | Right/left/u-turn/other unsafe turning (1), others (0) |
| | | Changing/merging lanes | Changing lanes or merging (1), others (0) |
| | | Ran off road | Ran-off road or cross into opposing lane (1), others (0) |
| | | Crossed into opposing lane | Crossed into opposing lane (1), others (0) |
| | | Passing other vehicle | Passing other vehicle (1), others (0) |
| | | Proceeding straight | Proceeding straight (1), others (0) |
| | | Other movements | Other movements (1), others (0) |
| Collision | Season | Spring | Crash occurred in April or May (1), others (0) |
| | | Summer | Crash occurred from June to August (1), others (0) |
| | | Autumn | Crash occurred in September or October (1), others (0) |
| | | Winter | Crash occurred from November to March (1), others (0) |
| | Day of week | Crash occurred on Weekend (1), Crash occurred on Weekdays (0) | |
| | Time of hour | Nighttime | Crash occurred between 0 h and 5 h (1), others (0) |
| | | Peak hour | Crash occurred 6–8 h, 16–18 h (1), others (0) |
| | | Non-peak hour | Crash occurred 9–15 h, 19–23 h (1), others (0) |
| | Road class | Local | Crash occurred on local road (1), others (0) |
| | | Interstate | Crash occurred on interstate highway (1), others |
| | | US highway | Crash occurred on US highway (1), others (0) |
| | | State route | Crash occurred on State route (1), others (0) |
| | | County road | Crash occurred on County road (1), others (0) |
| | Weather | Inclement weather | Rain/snow/fog/wind weather (1), others (0) |
| | Collision location | Intersection | Intersection (1), others (0) |
| | | Ramp or collector | Ramp or collector (1), others (0) |
| | | Highway | Highway (1), others (0) |
| | | Not state highway | Not state highway (1), others (0) |
| | Ramp intersection | Crash occurred at ramp exit (1), others (0) | |
| | | Crash occurred in mid-ramp (1), others (0) | |
| | | Crash occurred at ramp entry (1), others (0) | |
| | | Crash occurred in ramp related area within 100 ft (1), others | |
| | | Crash occurred at intersection (1), others (0) | |
| | Number of parties | Multi-vehicles involved | Multi-vehicle parties involved in the collision (1), single-vehicle party involved in the collision (0) |
| | Collision type | Head-on | Head-on type collision (1), others (0) |
| | | Sideswipe | Sideswipe type collision (1), others (0) |
| | | Rear-end | Rear-end type collision (1), others (0) |
| | | Broadside | Broadside type collision (1), others (0) |
| | | Hit object | Hit object type collision (1), others (0) |
| | | Overturned | Overturned type collision (1), others (0) |
| | Road surface | Not dry pavement | Wet/snowy/icy/muddy/oily (1), dry (0) |
| | Road condition | Holes, deep ruts | Holes, deep ruts road condition (1), others (0) |
| | | Loose material | Loose material on roadway (1), others (0) |
| | | Obstruction | Obstruction on roadway (1), others (0) |
| | | Construction zone | Construction or repair zone (1), others (0) |
| | | Other condition | Other unusual conditions (1), others (0) |
| | Lighting | Dusk/Dawn | Dusk or dawn (1), others (0) |
| | | Dark-street light | Dark with street light (1), others (0) |
| | | Dark-no street light | Dark without no street light (1), others (0) |
| | Truck involved | If the collision involved a truck (1), otherwise (0) | |

*Note.* Explanatory variables are equivalent through three age groups. Season is classified based on both average monthly temperature and precipitation in California.

As shown in Fig. 1, motorcyclists aged 54 years and younger have seen a considerable rise in fatal injuries since 1995. Considering the recent trend of fatalities, motorcyclists aged 45–54 years old had the highest increase in fatality rate since 2005, followed by motorcyclists aged 24 years and younger, when compared to the fatality rate increase prior to 2004. Motorcyclists aged 35 to 44 years old had relatively constant fatalities throughout the same time periods. The fatality rates of motorcyclists aged 25–34 were not examined in this study because the trend in this age group was less obvious.

For injury estimation of motorcyclists by age group, SWITRS datasets for collision, party, and victim for each age group from 2005 to 2009 were joined by case identification number to create a single dataset. The single dataset was filtered by (1) victim type, including motorcycle driver and motorcycle passenger only; (2) driver type of motorcycle party, only excluding parked vehicles; and (3) motorcycle-involved collisions only. Tables 1 and 2 summarizes descriptive statistics of variables and the resultant corresponding codes, respectively.

**Table 3**
MNL Model estimated for injury severities of motorcyclists by age group.

| Model fit | Less than 25 | | | | 35–44 | | | | 45–54 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| LR value (p-value) | 8822.2445 (<.0001) | | | | 6764.859 (<.0001) | | | | 6481.220 (<.0001) | | | |
| $\rho^2$ | 0.213 | | | | 0.204 | | | | 0.209 | | | |
| Variable | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 |
| Constant | −7.289 | −3.493 | −0.613 | −1.456 | −4.516 | −1.405 | 0.488 | 0.254 | −4.146 | −1.142 | 0.636 | 0.290 |
| Driver type of victim | 1.769 | 1.314 | 1.179 | 1.0430 | – | – | – | – | – | – | – | – |
| Female | −0.810 | – | −0.177 | – | – | – | – | – | −0.695 | −0.484 | −0.420 | −0.171 |
| *Not helmet used* | 0.666 | 0.768 | 0.767 | 0.689 | 0.681 | 0.871 | 0.877 | 0.863 | 0.457 | 0.704 | 0.592 | 0.568 |
| *Victim ejected* | 6.493 | 5.541 | 5.051 | 4.596 | 6.293 | 5.547 | 5.040 | 4.547 | 6.317 | 5.337 | 4.806 | 4.301 |
| At-fault party | 0.659 | – | – | – | – | – | – | −0.297 | – | – | – | −0.161 |
| *Alcohol/drug effect* | 2.128 | – | – | −0.922 | 2.536 | – | – | −0.782 | 2.173 | – | – | −0.951 |
| *Speeding violation* | 0.599 | 0.422 | – | – | | 0.497 | – | – | | 0.686 | 0.484 | |
| Improper turning | – | – | – | −0.708 | −0.956 | – | – | – | – | – | – | – |
| *Stop/slow movement* | −1.103 | −0.903 | −0.609 | – | −1.046 | −1.205 | −0.860 | −0.228 | −1.179 | −1.098 | −0.890 | −0.274 |
| *Turning movement* | −2.260 | −0.704 | −0.576 | −0.320 | −1.737 | −0.683 | −0.604 | −0.366 | −1.395 | −0.744 | −0.456 | – |
| Changing/merging lanes | – | −0.619 | – | −0.394 | – | – | – | – | – | – | – | – |
| Ran off road | – | – | −0.422 | – | – | – | −0.544 | – | 0.453 | – | – | 0.349 |
| Crossed into opposing lane | 0.938 | – | – | – | 1.520 | – | – | – | – | – | – | – |
| Season of winter | – | – | −0.255 | – | −0.460 | −0.299 | −0.285 | – | – | – | −0.232 | – |
| Season of summer | – | – | – | – | – | – | 0.1557 | – | – | – | 0.1502 | – |
| Weekend | 0.275 | 0.336 | 0.147 | – | – | 0.264 | – | – | 0.254 | 0.384 | 0.240 | 0.145 |
| Nighttime | – | | −0.293 | – | 0.512 | – | – | – | – | – | – | – |
| Non-peak | – | 0.208 | −0.156 | – | – | – | – | – | – | – | – | – |
| Multi-vehicles involved | – | −1.039 | −0.923 | −0.893 | – | −1.186 | −1.194 | −1.080 | −0.629 | −1.332 | −1.260 | −1.440 |
| *Head-on crash* | 0.645 | 1.063 | −0.426 | – | 1.357 | 0.765 | – | – | 1.638 | 0.806 | −0.426 | – |
| *Sideswipe crash* | −1.433 | – | −0.397 | – | −1.401 | −0.440 | −0.476 | – | −0.670 | – | −0.469 | – |
| Rear-end crash | −0.978 | – | −0.725 | – | – | – | −0.479 | – | −0.861 | – | −0.586 | – |
| *Broadside crash* | 0.905 | 0.852 | −0.270 | 0.382 | 0.968 | 0.758 | – | – | 0.527 | 0.604 | – | 0.464 |
| *Hit object crash* | 1.124 | 0.383 | −0.216 | – | 0.969 | – | – | – | 0.514 | – | −0.355 | −0.421 |
| Local road | 0.624 | 0.815 | 0.681 | 0.622 | 0.446 | 0.451 | 0.641 | 0.576 | – | 0.399 | 0.618 | 0.708 |
| County road line/area | – | 0.653 | 0.219 | – | – | 0.436 | – | 0.227 | – | 0.375 | 0.234 | 0.296 |
| *Wet, snow, icy, slippery surface* | −1.873 | – | −0.506 | – | −0.920 | −0.792 | −0.767 | −0.503 | −1.447 | −1.068 | −0.825 | −0.508 |
| Dark-street light | – | – | – | – | – | – | – | – | – | 0.208 | – | – |
| *Truck involved* | 2.056 | 1.134 | – | – | 1.679 | 0.611 | – | – | 1.665 | 0.784 | – | – |

*Note.* 1 = fatality; 2 = severe injury; 3 = other visible injury; 4 = complaint of pain injury; no injury is base case. *P*-value of 0.05 was employed for parameter estimate significance. – indicates insignificant coefficient. Italics indicate the variables simultaneously significant to fatality through all of three age groups.

## 5. Results and discussion

Multinomial logit model estimations were provided in Table 3. Two goodness-of-fit statistics were used: log-likelihood ratio (LR) and $\rho^2$. The LR value is the chi-squared value in the log-likelihood ratio test for the global null hypothesis test that reveals whether or not a global null hypothesis with a constant-only model should be rejected compared to an estimated model; the $\rho^2$ is an overall model fit defined as one minus the ratio of the log-likelihood at convergence with coefficients to the log-likelihood with a zero coefficient.

In the MNL model estimations, the following risk factors were found to be significant to motorcyclist injury severities: victim's personal information, victim's helmet use, victim ejection, at-fault party, alcohol/drug effects, party violation, action before collision, temporal information related to collision, number of parties involved in the collision, collision type, road classification, pavement surface condition, lighting condition, and truck involvement. Pseudo-elasticity of each significant indicator for the three age groups was provided in Table 4. For the purpose of this study, only the risk factors significantly affecting an increase in motorcyclist fatality were taken into account.

According to Tables 3 and 4, the following risk factors were more likely to increase motorcyclist fatality, regardless of age group: helmet use, victim ejection, alcohol or drug effects, collisions (including head-on, broadside, hit-object types), and truck involvement. Specifically, pseudo-elasticity of the alcohol/drug influence factor had the strongest extent of impact on motorcyclist fatalities across all age groups: 1052% for the older age group, 1286% for the middle age group; and 835% for the younger age group. This result implies public education strategies regarding sobriety should be enhanced to reduce motorcyclist injury severities across all three age groups.

Victim ejection also influenced a pronounced increase in motorcyclist fatalities for all age groups. Victim ejection was found to increase the probability of motorcyclist fatalities by 545% for older age group, 409% for the middle age group; and 920% for the younger age group. The effect of victim ejection is relatively consistent with the effect of no use of helmet, even though the extent of the impact for no use of helmet was found to be much smaller. These results imply that safety equipment or external roadway facilities that absorb collision impacts may reduce motorcyclist fatality.

As shown in Table 4, the truck involvement indicator was a significant factor, increasing fatalities by approximately 538% for the younger age group, 285% for middle-aged motorcyclists, and 337% for the older-aged motorcyclists.

Collision type was one of the strongest factors in increasing motorcyclist fatalities for all age groups. Head-on collisions were more likely to increase fatalities by 96% for the younger age group, 301% for the middle-aged group and 445% for the older age group. The effects of head-on collisions were the strongest in the older age group. The impacts of broadside and hit object collisions were comparatively stronger in increasing the probability of fatalities in the younger age group. Considering the impacts of collision type identified in Table 4, the strategies of roadway design improvement including roadway delineation, fence, or cushion might be helpful in reducing fatalities in younger and older riders.

**Table 4**
Pseudo-elasticity of variable (%).

| Variable | Less than 25 age group | | | | | 35–44 age group | | | | | 45–54 age group | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1.0 | 2.0 | 3.0 | 4.0 | 5.0 | 1.0 | 2.0 | 3.0 | 4.0 | 5.0 | 1.0 | 2.0 | 3.0 | 4.0 | 5.0 |
| Driver type of victim | **199** | **90** | **66** | **45** | −49 | – | – | – | – | – | – | – | – | – | – |
| Female | **−54** | −8 | **−13** | 12 | 4 | – | – | – | – | – | **−34** | **−53** | **−32** | **47** | 82 |
| Not helmet used | **30** | **44** | **44** | **33** | −33 | **−4** | **16** | **17** | **15** | −51 | **0** | **−25** | **−10** | **48** | −13 |
| Victim ejected | **920** | **294** | **141** | **53** | −98 | **409** | **142** | **46** | **−11** | −99 | **545** | **41** | **11** | **14** | −98 |
| At-fault party | **97** | 18 | −2 | −6 | 2 | 26 | 18 | 2 | **−16** | 12 | 34 | −27 | −17 | **20** | 47 |
| Alcohol/drug effect | **835** | 32 | 0 | **−56** | 11 | **1286** | 52 | 17 | **−50** | 10 | **1052** | −15 | −14 | **−33** | 80 |
| Speeding violation | **71** | **43** | 11 | −6 | −6 | 40 | **40** | 8 | −6 | −15 | 47 | **−30** | **−6** | 29 | 2 |
| Improper turning | −28 | 29 | −16 | **−42** | 18 | **−52** | 12 | 2 | −24 | 25 | −43 | −12 | −14 | 15 | 34 |
| Stop/slow movement | **−60** | **−52** | **−35** | 5 | 19 | **−47** | **55** | **−37** | **19** | 49 | **−50** | **−68** | **−48** | **64** | 123 |
| Turning movement | **−87** | **−40** | **−32** | **−12** | 21 | **−75** | **−28** | **−22** | **−1** | 43 | **−66** | **−62** | **−32** | 49 | 88 |
| Changing/merging lanes | −17 | **−40** | −8 | **−25** | 11 | – | – | – | – | – | – | – | – | – | – |
| Ran off road | 64 | 1 | **−24** | −11 | 16 | 14 | 23 | **−25** | 5 | 29 | **48** | −33 | −33 | **76** | 29 |
| Crossed into opposing lane | **180** | 49 | −17 | −9 | 9 | **299** | 54 | −16 | 17 | −13 | – | – | – | – | – |
| Season of winter | −5 | −5 | −17 | **13** | 7 | **−29** | **−16** | **−15** | 12 | 13 | −3 | −46 | −31 | **61** | 53 |
| Season of summer | – | – | – | – | – | −19 | 1 | **11** | −10 | −5 | 3 | −34 | −11 | **19** | 35 |
| Weekend | **23** | **31** | **9** | 3 | −6 | −1 | **21** | 3 | −2 | −7 | **12** | **−26** | **−14** | **33** | 19 |
| Nighttime | 0 | 38 | **−17** | −12 | 11 | **82** | 44 | −15 | 3 | 9 | – | – | – | – | – |
| Non-peak | 21 | **29** | **−10** | 0 | 5 | – | – | – | – | – | – | – | – | – | – |
| Multi-vehicles involved | 77 | **−52** | **−46** | **−44** | 37 | 40 | **−37** | **−37** | **−30** | 107 | **29** | **−63** | **−46** | **−24** | 233 |
| Head-on crash | **96** | **197** | **−33** | 39 | 3 | **301** | **122** | −20 | −3 | 3 | **445** | **38** | **−46** | 50 | 46 |
| Sideswipe crash | **−74** | 3 | **−26** | 17 | 10 | **−68** | **−17** | **−20** | 7 | 28 | **−37** | −41 | **−40** | 68 | 70 |
| Rear-end crash | **−55** | 18 | **−42** | 13 | 19 | −27 | 8 | **−24** | 12 | 22 | **−46** | −45 | **−45** | 78 | 75 |
| Broadside crash | **144** | **132** | **−25** | **45** | −1 | **138** | **93** | −18 | 11 | −10 | **50** | **−6** | −41 | **86** | 22 |
| Hit object crash | **226** | **55** | **−15** | 1 | 6 | **191** | 41 | −9 | −6 | 10 | **123** | −23 | **−27** | **16** | 83 |
| Local road | **31** | **58** | **39** | **31** | −30 | **−4** | **−3** | **17** | **9** | −39 | −26 | **−47** | **−11** | **64** | −16 |
| County road line/area | −23 | **73** | **12** | 6 | −10 | 0 | **30** | 1 | **5** | −16 | −11 | **−29** | **−18** | **48** | 14 |
| Wet, snow, icy, slippery surface | **−82** | −18 | **−31** | 9 | 15 | **−37** | **−29** | **−27** | **−5** | 57 | **−60** | **−66** | **−41** | **37** | 136 |
| Dark-street light | – | – | – | – | – | – | – | – | – | – | 12 | **−22** | −27 | 42 | 49 |
| Truck involved | **538** | **154** | 26 | −2 | −18 | **285** | **32** | 10 | 0 | −28 | **337** | **5** | −23 | 37 | 14 |

*Note.* 1 = fatality; 2 = severe injury; 3 = other visible injury; 4 = complaint of pain injury; 5 = no injury. Bold indicates the elasticity of each significant parameter estimate to injury levels. – indicates an inapplicability.

Compared to the middle-aged group, fatalities were more likely to increase on the weekends in the younger and older age groups by 23% and 12%, respectively. The non-peak hour time frame was also a factor that increased the likelihood of severe injuries in the younger age group. Based on these resultant findings, temporal traffic control policies would be effective in reducing fatalities for both younger and older motorcyclists.

Crossing into an opposing lane significantly increased the likelihood of fatality in the younger age group by 180%, asserting that younger drivers may be more likely to drive aggressively. The effect of running off road preceding a collision was also shown to significantly increase fatalities by 48% for the oldest age group. Additionally, multi-vehicle involvement in a collision was found to increase the likelihood of fatality by 29% for motorcyclists aged 45–55. The effects of running off road and the number of vehicles involved in a collision imply that older riders' are physically weaker or require more response/reaction time. Accordingly, clear roadway design and roadway facilities such as medians and crash cushions, especially for older-aged motorcyclists, can effectively reduce the fast-growing fatalities in these two age groups.

One of the California SHSP strategies for motorcycle safety is to improve motorcyclist visibility of other roadway users. As the relevant risk factor, street lights in the dark were found to decrease the probability of severe injury by 22 percent in the older age group. Considering that severe injury is more likely to lead to fatality, this result implies that street lights would help to improve motorcyclist visibility in weak-sighted road users who are more commonly of older age.

Driver-related factors of driver type of victim and at-fault driver were found to significantly increase the probability of fatalities in younger age groups by 199% and 97%, respectively. Local road, a road classification factor, increased the likelihood of fatality by 31% only in the younger age group. Speeding violations also increased the likelihood of fatality in the younger age group. Driver education and training, especially regarding speed violations and local road driving, are recommended to improve motorcycle safety for younger riders.

## 6. Conclusions and future extension

The goal of California's SHSP with regard to motorcycle safety was to decrease the number of motorcycle rider fatalities by 10 percent from the 2004 level to 2010. However, motorcycle fatalities in California have continuously increased since 1998, and the goal has not yet been achieved. The most visible trend in California is the disparity in fatalities between the age groups. Recently, older riders aged 45–54 showed the fastest growth in fatalities among all motorcyclists, while younger riders aged 25 and younger had the second fastest growth in fatalities. On the other hand, the number of motorcycle fatalities for those aged 35–44 has been relatively stable. The number of fatalities for each of the three motorcyclist groups accounts for a considerable portion of total fatalities that have occurred in California since 1995.

Based on the trends of California motorcycle fatalities, this paper quantitatively assessed and compared impacts of factors on motorcycle fatalities involving three age groups and evaluated the relevant safety strategies particular to reducing fatalities in motorcyclists aged 24 and younger and those aged 45–54. To achieve the research objective, standard multinomial logit models were estimated for motorcycle injuries (especially for fatalities) and pseudo-elasticity of each significant variable was calculated. As a result, key findings are provided as follows:

- Regardless of age group, motorcyclists were more likely to be fatally injured from the following risk factors: lack of or improper use of helmet, victim ejection, alcohol/drug effects, collisions (including head-on, broadside, hit-object types), and truck involvement. In particular, the impacts of victim ejection, alcohol or drug use, and truck involvement were more likely to increase motorcyclist fatalities.

- As temporal risk factors, the effects of weekend and non-peak hours on increasing fatalities were significant in both younger and older age groups.
- Running off-road preceding collision and multi-vehicle involvement were found to be statistically significant in increasing the probability of fatalities for older motorcyclists.
- Use of nighttime street lights was found to decrease the probability of severe injuries for older motorcyclists.
- Type of victim, at-fault driver, local road, and speed violation were identified as statistically significant in increasing motorcyclist fatalities in the younger age group.
- Road conditions including holes, deep ruts, loose material, and obstruction, as well as collision location factors such as intersections, ramps and highways were not found to be statistically significant in motorcyclist fatalities.

When taking the key findings into account, the six current CA SHSP implementation strategies were evaluated. Appropriate action items are proposed as follows:

- Public education regarding alcohol use and helmet use are extensively applicable to reducing motorcyclist fatalities.
- Enforcing the heavy vehicle violation is considered a widely effective strategy in reducing motorcyclist fatalities.
- Roadway facility strategies such as median, fence or crash cushion implementation to absorb collision impact are proposed as reasonable ways to reduce fatalities in all age groups.
- Roadway design factors such as clear and simple roadway delineation and visibility enhancement strategies are expected to be reasonable in reducing older motorcyclist fatalities in particular.
- Driver education and enforcement of speed violations are expected to improve motorcycle-related safety for younger motorcyclists in particular.

For future research, in-depth geometric design on local roads where motorcycle-related crashes occurred most frequently should be further analyzed to facilitate motorcyclist safety improvements. Road alignment data such as a curve or grade as well as data regarding the period of time in which motorcycle drivers have a license were deficient in this study. These data would help to further examine the impact of modifiable risk factors and the reliability of the resultant findings. It would also be valuable to compare several data mining techniques with the MNL model results to solidify strategies for motorcyclist safety improvements.

Interestingly, roadway surface conditions such as potholes, rutting, and surface roughness were not found to be significant in the estimated MNL models across all three age groups. Additionally, impacts of roadway surface conditions on fatalities were shown to be weak for all three age groups. However, California SHSP addresses roadway surface conditions as one of the key action items in reducing motorcyclist fatalities (Kempton et al., 2006). Additional research that assesses the implications of pavement surface conditions on roadway safety is necessary to support those specific actions in the California SHSP.

Fatalities of motorcyclists aged 25–34 have been gradually increasing and the present fatality figure is rather large. Accordingly, further research should examine the impacts of road conditions and other variables on fatalities in this age group.

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