Crash risk by driver age, gender, and time of day using a new exposure methodology☆,☆☆

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ABSTRACT

Introduction: Concerns have been raised that the nonlinear relation between crashes and travel exposure invalidates the conventional use of crash rates to control for exposure. A new metric of exposure that bears a linear association to crashes was used as basis for calculating unbiased crash risks. This study compared the two methods – conventional crash rates and new adjusted crash risk – for assessing the effect of driver age, gender, and time of day on the risk of crash involvement and crash fatality. *Method:* We used police reports of single-car and multi-car crashes with fatal and nonfatal driver injuries that occurred during 2002–2012 in Great Britain. *Results:* Conventional crash rates were highest in the youngest age group and declined steeply until age 60–69 years. The adjusted crash risk instead peaked at age 21–29 years and reduced gradually with age. The risk of nighttime driving, especially among teenage drivers, was much smaller when based on adjusted crash risks. Finally, the adjusted fatality risk incurred by elderly drivers remained constant across time of day, suggesting that their risk of sustaining a fatal injury due to a crash is more attributable to excess fragility than to crash seriousness. *Conclusions:* Our findings demonstrate a biasing effect of low travel exposure on conventional crash rates. This implies that conventional methods do not yield meaningful comparisons of crash risk between driver groups and driving conditions of varying exposure to risk. The excess crash rates typically associated with teenage and elderly drivers as well as nighttime driving are attributed in part to overestimation of risk at low travel exposure. *Practical Applications:* Greater attention should be directed toward crash involvement among drivers in their 20s and 30s as well as younger drivers. Countermeasures should focus on the role of physical vulnerability in fatality risk of elderly drivers.

1. Introduction

Road traffic collisions are a major global health concern. They account for more than 1.2 million deaths worldwide each year and an even larger number of serious injuries (World Health Organization, 2015). Obtaining a better understanding of the factors that contribute to driver crash risk is critical for the development of effective road safety policies and initiatives.

A wealth of road safety research has assessed driver characteristics, such as age and gender, linked to elevated crash risk. These studies have typically shown that the youngest and oldest drivers have much higher fatal and non-fatal crash risks than drivers in the middle-age ranges (Lam, 2002; Ma & Yan, 2014; McAndrews, Beyer, Guse, & Layde, 2013; Williams, 2003; Williams & Shabanova, 2003; Zhou, Zhao, Pour-Rouholamin, & Tobias, 2015). Several studies have also found differences in fatal and nonfatal crash risks among subgroups of older drivers. For example, there is evidence that drivers aged 70–74 exhibit lower crash risk relative to drivers aged 75–79, with the highest risk seen in drivers aged 80 and older (Cheung & McCartt, 2011; Cicchino, 2015; Cicchino & McCartt, 2014).

Road safety research has also addressed associations between driver gender and elevated crash risk. In general, female drivers are considered safer than male drivers (Åkerstedt & Kecklund, 2001; Kim, Brunner, & Yamashita, 2008; Ma & Yan, 2014; Massie, Green, & Campbell, 1997; Zhou et al., 2015). However, some studies suggest that while women tend to have fewer fatal crashes than men do, their risk of injury crashes may be higher (Massie, Campbell, & Williams, 1995; Santamariña-Rubio, Pérez, Olabarria, & Novoa, 2014).

In addition to crash involvement, driver's age and gender have also been shown to affect the severity of crash outcomes (i.e. the risk of fatal injury given a crash). Male and elderly drivers are more likely to be fatally injured in a crash than female drivers and drivers in the

younger age ranges (Huang & Lai, 2011; Kim, Ulfarsson, Kim, & Shankar, 2013; Li, Braver, & Chen, 2003; Valent et al., 2002; Vorko-Jović, Kern, & Biloglav, 2006).

The risk of crash involvement also appears to vary with environmental factors, such as time of day. Crash risk is higher for nighttime compared with other times of day, with the difference being more pronounced for male drivers and at younger ages (Doherty, Andrey, & MacGregor, 1998; Kim et al., 2013; Li, Baker, Langlois, & Kelen, 1998; Massie et al., 1995). Time of day has also appeared to be associated with crash severity, as drivers are more likely to sustain a fatal injury due to nighttime crashes compared to daytime crashes, particularly among the younger age groups (Huang & Lai, 2011; Valent et al., 2002; Vorko-Jović et al., 2006).

It is well recognized that in order to allow for meaningful comparisons of crash risk among driver groups or driving environments, it is necessary to take into account their differences in intensity of travel exposure (Elander, West, & French, 1993; Wolfe, 1982). If travel exposure is not controlled for, one cannot determine whether a higher number of crashes for a particular group (or environment) is due to a greater tendency for crash involvement or to greater exposure to travel situations that may result in a crash (Chapman, 1973; Muhlrad & Dupont, 2010).

Traditionally, researchers have accounted for differences in exposure by dividing the crash counts of a particular driver group (e.g., age, gender) by either their annual travel (Li et al., 2003; Massie et al., 1995, 1997), their group size in number of licensed drivers (Chen et al., 2010; McAndrews et al., 2013), or a combination of travel and group size (Doherty et al., 1998; Li et al., 1998). However, the use of crash rate to account for differences in driving exposure is appropriate as long as crash counts increase proportionally with increased driving exposure. That is, when the association between crash frequency and driving exposure, known as the 'safety performance function,' is linear (Elander et al., 1993; Qin, Ivan, & Ravishanker, 2004). Crash rate can be defined as the slope of the line from the origins to a particular point on the safety performance function. If the safety performance function is non-linear, then crash rate will vary at different exposure levels. Consequently, crash rates would not allow for meaningful risk comparisons among driver groups or driving conditions with varying levels of exposure (Elander et al., 1993; Janke, 1991; Qin et al., 2004).

Importantly, numerous road safety researchers (Elander et al., 1993; Elvik, 2014; Janke, 1991; Langford, Methorst, & Hakamies-Blomqvist, 2006; Maycock, Lockwood, & Lester, 1991; Qin et al., 2004; see af Wåhlberg, 2009 for review) reported that the relationship between annual crash counts and driving exposure is in fact nonlinear. Specifically, the relationship is often described as following a broadly logarithmic curve, with an initial rapid increase in crash counts at low exposure levels followed by gradually slowing down and finally flattening out at high exposure levels. As a result, as the distance driven increases, the crash rate per distance driven declines. Thus, it is a common finding in the literature that low-mileage drivers have greater crash rate than high-mileage drivers (Alvarez & Fierro, 2008; Antin et al., 2017; Hakamies-Blomqvist, Raitanen, & O'Neill, 2002; Langford et al., 2006).

There are several possible explanations for the nonlinearity of the safety performance function. First, high-mileage drivers clock a greater proportion of their miles on freeways, whereas low-mileage drivers tend to restrict their travel to relatively hazardous urban roads (Hakamies-Blomqvist et al., 2002; Janke, 1991; Keall & Frith, 2004, 2006). Second, high-mileage drivers accumulate greater driving experience than low-mileage drivers and therefore may possess better driving skills (Elander et al., 1993; Elvik, 2014). Finally, older drivers with visual or physical impairments tend to reduce their driving exposure (Alvarez & Fierro, 2008; Stutts, 1998); thus, a low-mileage group might include a larger number of impaired drivers who are more inclined to be involved in crashes (Keall & Frith, 2004; Langford et al., 2006, 2013).

Regardless of the underlying reasons, the exposure–crash relationship is nonlinear, and hence crash rates become smaller with increased driving exposure. Because of this, concerns have been raised in the road safety literature that the use of crash rates may lead to biased risk comparisons when driver groups or driving conditions vary greatly in their travel exposure (Elander et al., 1993; Elvik, 2014; Hauer, 1995; Janke, 1991; Qin et al., 2004). Accordingly, differences in crash rate between groups or driving conditions may reflect variation in exposure rather than variation in crash tendency. Consequently, the rate-based method may lead to overestimation of crash risk for low-exposed drivers, and underestimation for high-exposed drivers (for similar reasoning against the use of rates to control for exposure to risk applied to biological and epidemiological data see Allison, Paultre, Goran, Poehlman, & Heymsfield, 1995; Curran-Everett, 2013; Packard & Boardman, 1999).

A common finding in the literature is that young and elderly drivers have lower driving exposure than other age groups in terms of distance traveled and number of license holders (e.g., Fontaine, 2003; Keall & Frith, 2006; Langford et al., 2006). It follows that in the case of age group comparisons, the use of crash rates may lead to underestimation of crash risk for low-exposed age groups, such as young and elderly drivers, and overestimation of crash risk for high-exposed age groups, such as drivers in the middle-age range. In line with this, the proportion of low-annual travel drivers as a function of age has a U-shaped curve similar to that typically observed for crash rate by age: Elevated values for younger and older drivers relative to the middle-aged drivers (Fontaine, 2003; Janke, 1991; Keall & Frith, 2006). This observation has led to the theoretical notion, referred to as 'low-mileage bias,' whereby the elevated crash risk among elderly drivers might be the result of their low distance traveled (Hakamies-Blomqvist et al., 2002). In accordance with this reasoning, comparing subgroups of drivers of different ages matched for distance driven has led to the oldest drivers being the safest or just as safe as drivers in other age ranges (Alvarez & Fierro, 2008; Fontaine, 2003; Hakamies-Blomqvist et al., 2002; Langford et al., 2006).

Biased estimation of crash rates might also occur for gender comparisons in crash risk. Studies have reported that women of all ages are less likely than men to have a driver's license, and those who do tend to drive lower annual mileage (Fontaine, 2003; Li et al., 1998; Massie et al., 1995; Santamariña-Rubio et al., 2014). It is conceivable then that the rate-based crash risk of female drivers might be underestimated, while their male counterparts might have an overestimated crash risk.

The use of crash rates can be equally regarded as inappropriate for any driving conditions that differ substantially in travel exposure, such as time of day. The proportion of night driving is considerably small across all ages, as most of the driving is done during daytime (Keall & Frith, 2004, 2006; Powell et al., 2007). For example, in one study, researchers found that only 13% of drivers' total driving distance was made at night (Keall & Frith, 2004). The small exposure to risk during nighttime hours may therefore be associated with biased estimates of crash rates, whereby nighttime crash risk is exaggerated relative to other times of day. Moreover, given that age and gender differences in travel exposure vary with time of day (e.g., Keall & Frith, 2004), disaggregating crash risk by time of day would be of relevance for risk comparisons among driver groups.

This paper aims to examine the extent to which the traditional crash rate approach is biased for risk comparisons between age–gender groups and across different times of day. To this end, we compared the results of conventional crash rates to those of adjusted risk estimators computed using a new exposure metric that provides a linear relationship for the safety performance function, as outlined below. We hypothesized that when using conventional crash rate estimators, young and elderly drivers would demonstrate a much higher risk of crash involvement for fatal and nonfatal crashes compared to drivers in the middle-age ranges; in contrast, when using adjusted risk estimators, age differences in crash involvement risk would be substantially reduced. Similarly, we hypothesized that the risk of crash involvement for nighttime driving compared to driving during the day and evening hours would be reduced when using the new adjusted risk estimators compared to the traditional crash rates.

As a further consideration, we also assessed the risk of crash fatality (i.e., driver fatal injury given a crash had occurred) as estimated by the traditional and adjusted methods. Fatality risk was defined as the ratio of fatal crash involvement risk to both fatal and nonfatal crash involvement risks. Our rationale was that if small driver numbers among the young and elderly and infrequent travel at night bias traditional assessments of crash risk, then any measures of fatal injury risk based on this approach would also be biased.

Single- and multi-vehicle crashes appear to differ substantially in their characteristics and contributing factors (Bingham & Ehsani, 2012; Williams & Shabanova, 2003). Furthermore, it has been argued that estimating crash risk of multi-vehicle collisions requires adjusting for the travel exposure of all drivers involved (Elvik, 2014; Qin et al., 2004; Rolison, Moutari, Hewson, & Hellier, 2014). Therefore, comparisons between conventional and adjusted crash risk methods were made separately for single- and two-vehicle crashes.

2. Materials and methods

2.1. Travel exposure data

Estimates of driving exposure in terms of trip numbers and license holders were obtained from the United Kingdom (UK) National Travel Survey for the periods of 2002–2012 (Department for Transport [DfT], 2012a). Trip numbers per driver were estimated annually for each driver age range (17–20, 21–29, 30–39, 40–49, 50–59, 60–69, ≥70 years), gender, and time of day (daytime 06:00–18:00; evening 18:00–21:00; nighttime 21:00–06:00). Driver numbers in the population were estimated annually for each age range and gender as the product of the proportion of drivers in the UK National Travel Survey sample (14,959 drivers on average, annually) and the estimated number of UK residents.

2.2. Road accident data

The road accident data were population-wide single- and two-car collisions reported in Great Britain (England, Scotland, and Wales) during the years 2002 through 2012. The road accident data were recorded by police officials on location and were made available by the University of Essex Data Archive after being processed by the Department for Transport (DfT, 2012b). Driver deaths occurring within 30 days following a road accident were classified as road accident fatalities. Non-fatal collisions included non-fatal driver injury cases.

2.3. Calculation for single-vehicle crashes

Traditional crash risk, γ_i, was estimated by dividing the crash counts, x_i, of each driver group, i, by the product of their estimated trips per driver, y_i, and their driver numbers in the population, z_i, where:

$$\gamma_i = \frac{x_i}{y_i \times z_i}. \tag{1}$$

The γ_i values were scaled annually by dividing each by the largest across all driver groups (i.e., age, gender, time of day), whereby γ_i was equal to 1 for the driver group with the highest crash risk.

Here, we employed the new exposure metric to provide a linear safety performance function and remedy the biasing effects of crash rates. This approach involves an alternative assessment of risk exposure. Accordingly, the adjusted exposure, ξ_i, of each driver group, i, is estimated on the assumption that exposure should be high if the population of a driver group is large and their trips are many, low if their population is large and their trips are few, and higher if their population is small and

their trips are many than if their population is small and their trips are few. It follows that:

$$\xi_i = \frac{\exp(2 \times \bar{z}_i) - \bar{y}_i \times (1 - \bar{z}_i)}{(1 - \bar{y}_i) + \exp(2 \times \bar{z}_i)}, \tag{2}$$

where total trips per driver, $\bar{y}_i$, and the population, $\bar{z}_i$, are scaled values that are calculated by dividing each value by the largest across driver groups (i.e., age, gender, time of day).

The adjusted crash risk, γ_i', of each driver group, i, is estimated on the assumption that the crash risk of a driver group should be high if their crashes are many and their adjusted exposure is small, low if their crashes are few and their exposure is high, and higher if their crashes are few and their exposure is low than if their crashes are many and their exposure is high. Thus:

$$\gamma_i' = \alpha \times A_i \times \frac{1 - (\xi_i - \bar{x}_i) \times \exp(-2 \times \bar{x}_i)}{1 + \exp(-2 \times \bar{x}_i)}, \tag{3}$$

with:

$$\alpha = \frac{\exp(1)}{1 - \exp(1)}, \tag{3a}$$

and:

$$A_i = 1 + \bar{x}_i \times \exp(-\bar{x}_i) - \xi_i \times \exp(\xi_i - 1), \tag{3b}$$

where crash numbers, $\bar{x}_i$, are scaled values that are calculated by dividing each value by the largest across all driver groups (i.e., age, gender, time of day). As for traditional crash risks, the adjusted crash risks, γ_i', were scaled annually by dividing each by the largest across all driver groups. Relative risks and 95% confidence intervals were calculated using beta regression analyses.

Fig. 1A plots the relationship between scaled conventional crash rate and exposure levels (with exposure defined as the product of trip numbers and population size). For comparison, Fig. 1B plots the relationship between the scaled adjusted crash risk and exposure levels based on the proposed exposure metric. These plots show that traditional crash rates are increased at the lowest exposure level with a rapid decrease and flattening out at higher exposure. In contrast, the adjusted crash risk remained constant with exposure, enabling comparison of driver groups that vary greatly in population numbers and amount of travel.

2.4. Calculation for multi-vehicle crashes

Traditional crash risk for two-car collisions was calculated using Eq. (1) in the same way as for single-car crashes. In order to calculate two-car adjusted crash risk, we employed the extended adjusted crash risk metric, which explicitly accounts for all drivers involved in multicar collisions. It follows that, for two-car crashes, adjusted crash risk, γ_i', is equal to the geometric mean of the adjusted crash risks across each of the other driver age ranges involved in the same collision, such that:

$$\gamma_i' = \left(\prod_{j=1}^{N} \alpha \times A_{ij} \times \frac{1 - \left(\xi_{ij} - \bar{x}_{ij}\right) \times \exp\left(-2 \times \bar{x}_{ij}\right)}{1 + \exp\left(-2 \times \bar{x}_{ij}\right)} \right)^{1/N}, \tag{4}$$

with

$$\alpha = \frac{\exp(1)}{1 - \exp(1)}, A_{ij} = 1 + \bar{x}_{ij} \times \exp(-\bar{x}_{ij}) - \xi_{ij} \times \exp\left(\xi_{ij} - 1\right), \xi_{ij}$$
$$= \sqrt{\xi_i \times \xi_j},$$

where N indicates the number of other driver age ranges involved in the same multiple car collision. As such, the adjusted two-car crash risk of each driver age range is aggregated after having adjusted for the risk
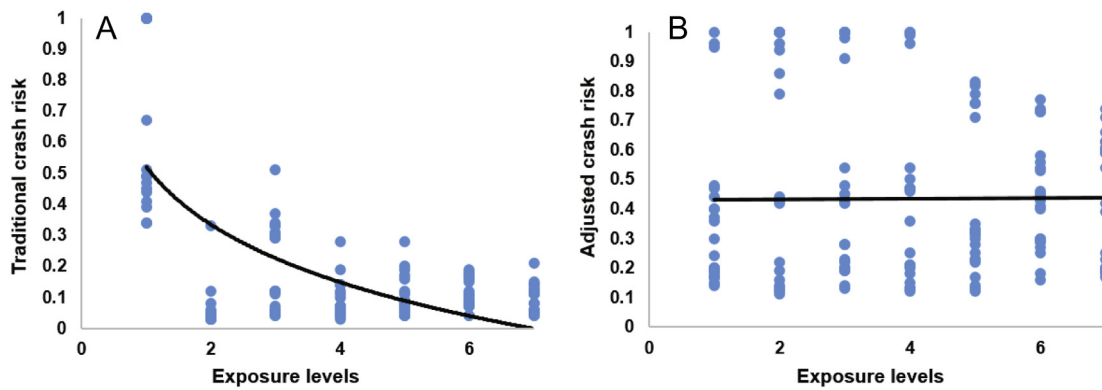
Fig. 1. Effects of increasing exposure levels based on conventional exposure estimates (A) and the new exposure metric (B) on traditional and adjusted crash risk.

exposure of all other drivers involved in each multicar collision. As in the single-car analysis, relative risks and 95% confidence intervals were calculated using beta regression analyses.

3. Results

3.1. Driving exposure estimates

In terms of population size, as expected, the youngest and oldest drivers were fewest in number in the population (Table 1). Specifically, drivers aged 17–20 years were 87% fewer in number and drivers aged 70 years and above were 46% fewer in number than drivers aged 40–49 years who represented the largest driver age group in the population. In terms of the amount of travel, Table 1 shows that, expectedly, trips per driver were fewest in number among men and women in the youngest age range of 17–20 years and in the oldest drivers aged 70 +. The average number of trips per driver was highest in the 50–59 age group for men and the 40–49 age group for women. For both genders, fewer trips were made at night than during daytime or evening. In fact, only 8% of trips taken by men and 5% of trips taken by women occurred at night.

3.2. Frequency of single-vehicle crashes

The 30–39 year age group had the highest frequency of daytime crashes, whereas the 21–29 year age group had the highest crash frequency during evening and night hours (Table 2). Crash numbers

decreased gradually with age to a minimum at 70 or more years, the exception being fatal crashes where there was a slight increase in the oldest age group. Men and women showed similar trends, but with lower frequency for women.

3.3. Single-vehicle crash involvement risk

Traditional rates of crash involvement by driver age and gender were calculated based on the estimated number of licensed drivers and trip numbers in each age–gender group. The youngest age group had an excess relative risk of being involved in fatal and nonfatal single-car crashes compared with the reference group aged 60–69 years (Table 3). Specifically, drivers aged 17 to 20, in both genders, had a nearly 19-fold the risk of fatal crash involvement compared to drivers aged 60–69 years. Similarly, the risk of non-fatal crash involvement for teen drivers was about 15 times as high as that of drivers aged 60 to 69. There was a steep decline in the relative risk of crash involvement with drivers' age, for both fatal and non-fatal crashes. The crash risk of female drivers aged 70 and over was 2.20 and 1.33 times as high as those of female drivers aged 60 to 69, for fatal and non-fatal crashes, respectively. Male drivers aged 70 and over had a fatal crash risk comparable with 60 to 60 year olds, and even showed 10% reduction in the relative risk for nonfatal crashes. Overall, with the exception of elderly drivers, the traditional method for calculating rate-based crash risks followed the familiar age pattern whereby young drivers have a much higher risk of crash involvement than other age groups.

Conversely, based on the adjusted risk estimators, relative risk for fatal and non-fatal crash involvement peaked at age 21–29 years for

Table 1
Estimated average annual trip and driver numbers in the population by age, gender, and time of day in Great Britain, 2002–2012.

	Trip numbers			Driver numbers
	Day	Evening	Night	
Males				
17–20	411	113	86	440
21–29	482	114	67	1,877
30–39	534	106	52	3,015
40–49	578	118	56	3,282
50–59	610	105	54	2,877
60–69	594	74	38	2,388
70 +	513	45	22	2,156
Females				
17–20	391	99	56	391
21–29	517	97	42	1,974
30–39	609	88	29	2,980
40–49	647	104	36	3,109
50–59	552	81	33	2,542
60–69	457	51	24	1,888
70 +	388	31	16	1,301

Note. Trip numbers are annual numbers per driver in the population; driver numbers are driver numbers in the population per 1,000 drivers.

Table 2
Single-car fatal and non-fatal crash counts by driver age, gender, and time of day in Great Britain, 2002–2012.

	Fatal crash counts			Nonfatal crash counts		
	Day	Evening	Night	Day	Evening	Night
Males						
17–20	16	10	44	2,081	938	2,251
21–29	35	16	66	4,101	1,347	2,616
30–39	40	16	35	4,702	1,218	1,637
40–49	28	10	19	4,251	948	1,112
50–59	17	7	12	3,086	591	578
60–69	12	2	5	1,682	286	234
70 +	19	2	2	1,188	155	101
Females						
17–20	3	1	6	949	342	568
21–29	6	2	7	2,069	539	610
30–39	6	2	4	2,228	426	324
40–49	6	1	2	1,831	333	215
50–59	3	1	1	1,079	182	108
60–69	2	0	0	553	79	40
70 +	6	0	0	474	50	22

Table 3
Traditional and adjusted single-vehicle crash risks for fatal and nonfatal collisions by driver age and gender in Great Britain, 2002–2012.

	Fatal relative risk		Nonfatal relative risk	
	Traditional	Adjusted	Traditional	Adjusted
Males				
17–20	18.6 [17.6–19.8]	1.79 [1.75–1.83]	15.3 [14.7–15.9]	1.67 [1.63–1.70]
21–29	8.50 [7.96–9.11]	2.54 [2.50–2.59]	5.46 [5.24–5.68]	2.17 [2.14–2.20]
30–39	3.88 [3.63–4.14]	2.44 [2.39–2.49]	2.95 [2.81–3.09]	2.08 [2.05–2.12]
40–49	2.01 [1.87–2.15]	1.79 [1.75–1.83]	1.91 [1.82–2.00]	1.75 [1.72–1.79]
50–59	1.59 [1.49–1.70]	1.39 [1.35–1.43]	1.34 [1.27–1.41]	1.34 [1.32–1.36]
60–69	1.00	1.00	1.00	1.00
70 +	0.90 [0.80–1.01]	1.12 [1.08–1.15]	0.90 [0.85–0.94]	0.92 [0.90–0.93]
Females				
17–20	18.8 [16.9–20.8]	0.94 [0.91–0.96]	14.8 [14.2–15.5]	1.19 [1.16–1.21]
21–29	5.63 [4.99–6.37]	1.19 [1.16–1.22]	4.44 [4.26–4.63]	1.65 [1.62–1.67]
30–39	3.38 [2.95–3.82]	1.39 [1.36–1.42]	2.46 [2.36–2.58]	1.67 [1.65–1.69]
40–49	1.77 [1.54–2.02]	1.24 [1.21–1.28]	1.52 [1.46–1.58]	1.45 [1.43–1.47]
50–59	1.74 [1.51–1.99]	1.13 [1.11–1.16]	1.20 [1.15–1.26]	1.18 [1.17–1.20]
60–69	1.00	1.00	1.00	1.00
70 +	2.20 [1.90–2.51]	1.03 [1.00–1.06]	1.33 [1.27–1.39]	0.94 [0.93–0.96]

Note. Crash risks were scaled annually by dividing their values by the largest across age and gender. Relative risks were estimated using beta regression analyses. Figures in parenthesis indicate the bootstrapped 95% confidence intervals. Drivers aged 60–69 years were used as the reference group.

men and at age 30–39 years for women. As illustrated in Table 3, the relative risk of fatal and nonfatal crash involvement was gradually reduced across driver age ranges. Relative to male drivers in the 60–69 age group, young male drivers aged 17 to 20 had only 1.79 and 1.67 times as much risk for fatal and nonfatal crash involvement, respectively. These relative risks of crash involvement for male teen drivers were about the same as those shown by middle-aged drivers and lower than those of drivers in their 20s and 30s. For females, teen drivers had 10% lower risk of being involved in a fatal crash and only 1.19 times as high risk of nonfatal crash involvement than drivers aged 60 to 69. Finally, the relative risk of the oldest female age group was comparable to 60–69 year olds for fatal crash involvement and even reduced by 6% for nonfatal crashes.

When crash involvement for age-gender groups was examined by time of day, it was found that nighttime crashes accounted for 80% (95% CI, 80%–81%) of the traditional single-car fatal crash risk for 17- to 20-year-old men and 85% (95% CI, 84%–86%) for women (Fig. 2A). To a lesser extent, nighttime crashes also accounted for a large proportion of teen drivers' non-fatal crash rates, with 66% (95% CI, 66%–66%) for men and 62% (95% CI, 62%–63%) for women (Fig. 2B). Hence, the traditional method of estimating driver crash risk indicates a high risk of driving at night among the youngest drivers relative to other times of the day.

In contrast, the adjusted crash risk metric revealed that crashes at night accounted for a much smaller proportion of the overall crash risk in the 17–20 year age range. Nighttime crashes accounted for 61% (95% CI, 60%–61%) of the adjusted fatal crash risk for men and 53% (95% CI, 53%–54%) for women (Fig. 2C). Just 47% (95% CI, 47%–47%) of the adjusted non-fatal crash risk of 17- to 20-year-old male drivers was accounted for by nighttime crashes, compared to 42% (95% CI, 42%–42%) for female drivers (Fig. 2D).

3.4. Single-car risk of fatal injury given crash involvement

The risk of fatal injury given crash involvement was measured as fatal crash risk divided by the sum of fatal and non-fatal crash risk. Fig. 3 shows the traditional and adjusted risk of fatal injury for each age range and gender during daytime, evening, and nighttime hours. Risk of fatal injury could range in value from 0 to 1. A value of 0.50 indicates that the fatal crash risk of a driver group relative to other groups is equal to the non-fatal crash risk relative to other groups. A value of greater than 0.50 indicates a higher relative risk of fatal injury given crash involvement and a value of less than 0.50 indicates a lower relative risk of fatal injury.

Age differences in the risk of sustaining a fatal injury differed depending on the method used to compute crash involvement risks. Risk of fatal injury based on traditional crash rates showed an increase from the 60–69 year group to the oldest age group in men during daytime and evening hours (Fig. 3A) and in women (Fig. 3B) during daytime, evening, and nighttime. In contrast, when based on adjusted
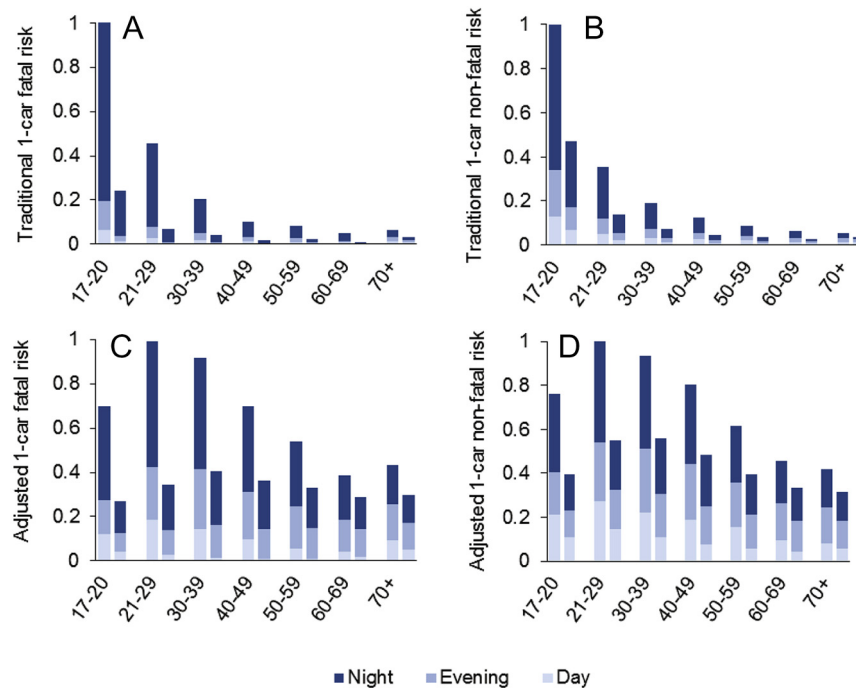

Fig. 2. Traditional single-vehicle fatal (A) and non-fatal (B) crash risk and adjusted single-vehicle fatal (C) and non-fatal (D) crash risk by driver age and gender stacked for daytime (06:00 h–18:00 h), evening (18:00 h–21:00 h), and nighttime (21:00 h–06:00 h) hours. Left and right columns represent male and female crash risks, respectively. Traditional and adjusted crash risks were each scaled annually by dividing their values by the largest across driver groups.
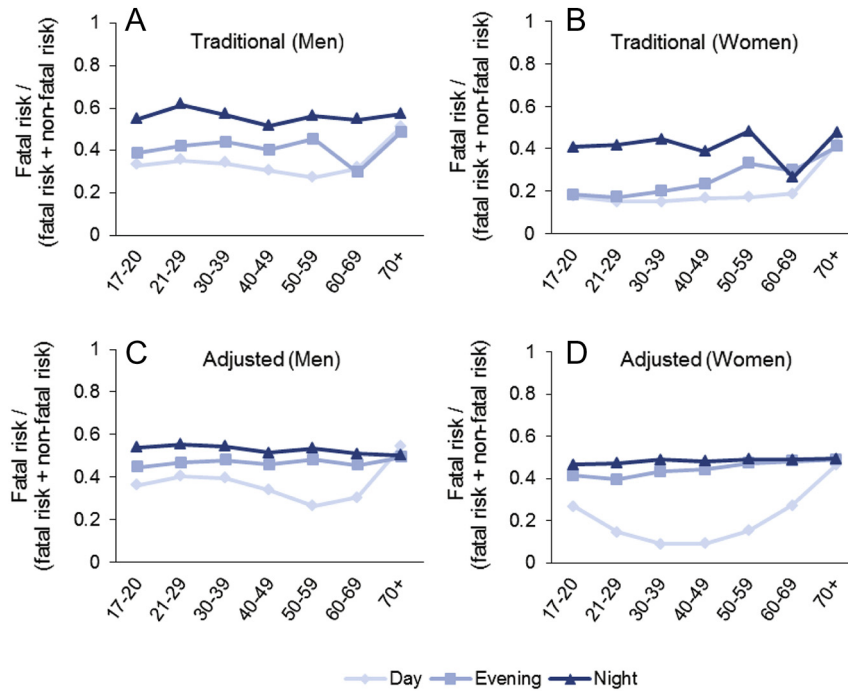
Fig. 3. Traditional and adjusted single-car risk of fatal injury given crash involvement by gender and driver age during daytime (06:00 h–18:00 h), evening (18:00 h–21:00 h), and nighttime (21:00 h–06:00 h) hours. Risk of fatal injury given crash involvement was calculated annually by dividing the single-car fatal crash risk by the sum of the single-car fatal and non-fatal crash risk.

crash risks, risk of fatal injury increased from age 60–69 years to the oldest age group only during daytime for both men (Fig. 3C) and women (Fig. 3D). Female drivers, particularly those in the 31–39 and 41–49 age groups, had a very low risk of fatal injury during daytime.

The risk of fatal injury based on traditional estimates was greater for nighttime crashes than for crashes in the evening and daytime hours, in both male (Fig. 3A) and female drivers (Fig. 3B). When based on the adjusted estimates, the risk of fatal injury for nighttime crashes was higher than that of daytime crashes, but similar to that of crashes occurring during evening hours, in both men (Fig. 3C) and women (Fig. 3D).

3.5. Frequency of two-vehicle crashes

As illustrated in Table 4, on average, multicar non-fatal crashes were greatest in number among 21 to 29-year-old men and women. The fatal crash frequency of women was greatest among 21–29 year olds,

whereas the fatal crash frequency of men was greatest in the 30–39 year age range. Non-fatal crash numbers declined with age to a minimum at 70 + years, whereas numbers of fatal crashes declined with age until a rise from age 60–69 years to age 70 + years. Fatal and non-fatal crashes were greater in number during the daytime for men and women than during evening or nighttime hours.

3.6. Multi-vehicle crash involvement risk

Traditional risk estimates for multi-vehicle fatal and non-fatal crash involvement were calculated by driver age and gender. Crash rates were highest among drivers aged 17 to 20 and reduced steeply with age (Table 5; Fig. 4A and B). The risk of crash involvement for teen male

Table 4
Two-vehicle fatal and non-fatal crash counts by driver age, gender, and time of day in Great Britain, 2002–2012.

	Fatal crash counts			Nonfatal crash counts		
	Day	Evening	Night	Day	Evening	Night
Males						
17–20	34	13	21	4,263	1,462	1,239
21–29	66	24	30	8,449	2,342	1,787
30–39	80	21	24	9,178	2,022	1,371
40–49	74	20	18	7,651	1,501	933
50–59	54	10	12	5,173	913	517
60–69	34	5	6	3,011	452	219
70 +	64	6	5	2,671	307	118
Females						
17–20	8	2	3	1,833	551	357
21–29	17	3	4	4,256	952	466
30–39	13	3	3	4,423	778	305
40–49	14	4	3	3,615	635	237
50–59	13	2	2	2,229	373	140
60–69	10	2	1	1,168	172	61
70 +	22	2	1	1,084	111	37

Table 5
Two-vehicle fatal and nonfatal crash risks based on traditional and adjusted crash risk, by driver age and gender in Great Britain, 2002–2012.

	Fatal relative risk		Nonfatal relative risk	
	Traditional	Adjusted	Traditional	Adjusted
Males				
17–20	7.75 [7.35–8.19]	0.98 [0.96–1.00]	11.1 [10.7–11.4]	1.10 [1.09–1.11]
21–29	3.23 [3.02–3.46]	1.22 [1.20–1.25]	4.56 [4.39–4.76]	1.44 [1.43–1.45]
30–39	2.04 [1.92–2.17]	1.34 [1.32–1.37]	2.74 [2.61–2.87]	1.45 [1.44–1.45]
40–49	1.51 [1.42–1.60]	1.33 [1.31–1.35]	1.76 [1.69–1.84]	1.34 [1.33–1.36]
50–59	1.15 [1.07–1.23]	1.10 [1.08–1.13]	1.28 [1.22–1.35]	1.12 [1.12–1.13]
60–69	1.00	1.00	1.00	1.00
70 +	1.75 [1.63–1.87]	1.13 [1.10–1.16]	1.12 [1.07–1.18]	1.01 [1.00–1.02]
Females				
17–20	3.68 [3.28–4.13]	0.86 [0.84–0.87]	8.73 [8.37–9.09]	0.95 [0.95–0.96]
21–29	1.31 [1.19–1.44]	0.97 [0.95–0.98]	3.05 [2.94–3.18]	1.16 [1.16–1.17]
30–39	0.92 [0.83–1.01]	1.12 [1.11–1.14]	1.87 [1.79–1.95]	1.28 [1.27–1.29]
40–49	0.77 [0.70–0.84]	1.10 [1.08–1.12]	1.27 [1.22–1.32]	1.20 [1.19–1.21]
50–59	0.68 [0.62–0.74]	1.02 [1.01–1.04]	1.11 [1.06–1.17]	1.08 [1.08–1.09]
60–69	1.00	1.00	1.00	1.00
70 +	2.29 [2.11–2.49]	1.01 [0.99–1.02]	1.46 [1.39–1.53]	0.97 [0.96–0.97]

Note. Crash risks were scaled annually by dividing their values by the largest across age and gender. Relative risks were estimated using beta regression analyses. Figures in parenthesis indicate the bootstrapped 95% confidence intervals. Drivers aged 60–69 years were used as the reference group.
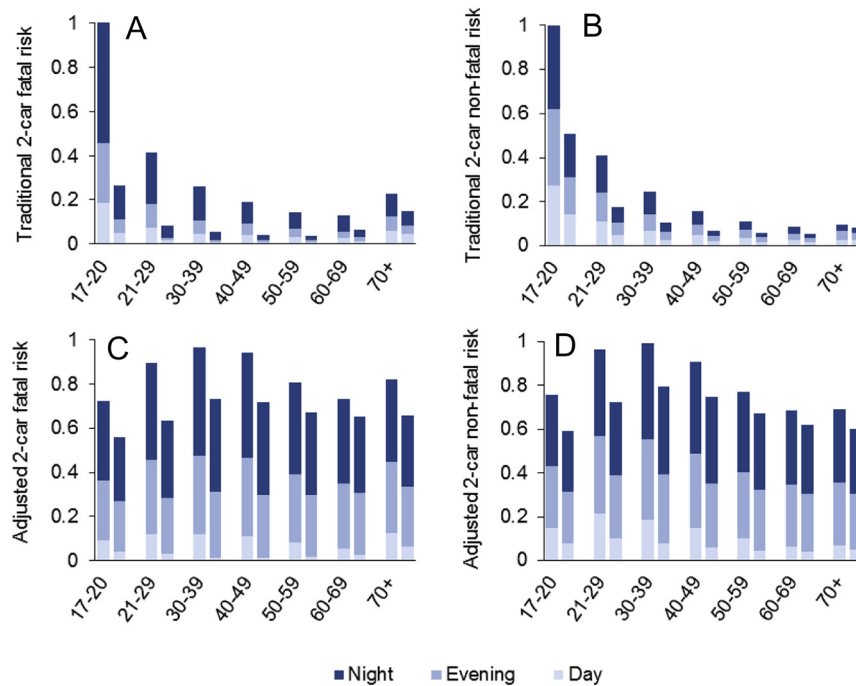
Fig. 4. Traditional 2-car fatal (A) and non-fatal (B) crash risk and adjusted 2-car fatal (C) and non-fatal (D) crash risk by driver age and gender stacked for daytime (06:00 h–18:00 h), evening (18:00 h–21:00 h), and nighttime (21:00 h–06:00 h) hours. Left and right columns represent male and female crash risks, respectively. Traditional and adjusted crash risks were each scaled annually by dividing their values by the largest across driver groups.

drivers was 7.75 and 11.1 times as high as the risk of drivers in the safest age group (60–69), for fatal and nonfatal crashes, respectively. Relative to 60–69 year olds, the crash risk of other age groups of male drivers varied between 1.15 and 3.23 for fatal crashes; and between 1.12 and 4.56 for nonfatal crashes. The oldest male group was 1.75 and 1.12 times as likely to be involved in fatal and nonfatal crashes respectively, as compared to the 60–69 age group.

For female teen drivers, the risk of being involved in a fatal crash was 3.68 times as high as that among female drivers aged 60 to 69. The 21–29 and oldest age groups had 1.31 and 2.29 times as high fatal crash risk as drivers aged 60 to 69. Fatal crash risk was reduced by 8% to 32% among female drivers in the middle age ranges (30s to 50s) in comparison to the 60–69 reference group. The risk of nonfatal crash involvement among female drivers was highest for the 17–20 year olds, who had a relative risk equal to 8.73; it then declined sharply with age up to the oldest age group, having 1.46 times the risk compared to the reference age group.

In contrast with the age trends in traditional crash risk, adjusted multicar fatal and non-fatal crash risk was highest among the 30–39 year age range and showed a gradual decline with age (Table 5; Fig. 4C and D). Compared with drivers aged 60 to 69, teen female drivers had 14% less risk of being involved in a fatal crash and 3% less risk of being involved in a nonfatal crash. For male teen drivers, their risk of fatal crash involvement was comparable to drivers aged 60 to 69, and they were only 1.10 as likely to be involved in a nonfatal crash. Female drivers aged 70 and over had similar or slightly reduced risk of being involved in a crash as drivers in the 60–69 age group. For males, the oldest group of drivers had only 1.13 times the risk of fatal crash involvement and their nonfatal crash risk was similar to that of drivers aged 60 to 69.

Comparisons of crash involvement risk by driver group across time of day revealed that crashes at nighttime accounted for 54% (95% CI, 54%–55%) of the traditional multicar fatal crash rates among 17 to 20-year-old men and 52% (95% CI, 50%–54%) among women (Fig. 4A) and accounted for 38% (95% CI, 38%–38%) of the traditional non-fatal crash risk for 17 to 20-year-old men and 38% (95% CI, 38%–39%) for women (Fig. 4B). Crash risks based on the adjusted method revealed a similar multicar crash risk during nighttime relative to other times of day.

Accordingly, nighttime crashes accounted for 50% (95% CI, 50%–50%) of the adjusted fatal crash risk for 17 to 20-year-old men and 52% (95% CI, 52%–52%) for women and 43% (95% CI, 43%–43%) of the non-fatal crash risk for men and 47% (95% CI, 47%–47%) for women.

3.7. Multicar risk of fatal injury given crash involvement

Risk of fatal injury based on traditional crash risks was greater in nighttime crashes than in crashes during daytime or evening hours among male (Fig. 5A) and female drivers (Fig. 5B). In contrast, based on the adjusted crash risks, the risk of fatal injury for nighttime crashes was similar to that of crashes occurring during evening hours, in both men (Fig. 5C) and women (Fig. 5D). Similarly, age differences in fatal injury risk differed depending on whether they were computed by the traditional or adjusted crash risks. Based on traditional crash rates, the risk of fatal injury increased from age 60–69 years to age >70 years during daytime, evening, and nighttime hours among men (Fig. 5A) and women (Fig. 5B). In contrast, the risk of fatal injury as measured by adjusted crash risks increased from age 60–69 years to age >70 years only during the daytime for men (Fig. 5C) and women (Fig. 5D). As in the single-vehicle analysis, female drivers' fatal crash risk was extremely low during the daytime, especially among those in their 30s and 40s.

4. Discussion

Crash rates are commonly used to assess the risk of different driver groups varying in exposure to risk. However, this approach requires that crash frequency and the exposure index be correlated linearly — an invalid assumption when using conventional measurement of exposure. Here we applied a crash risk method based on a new exposure metric, for which the number of crashes is proportional to the amount of driving exposure. We found that traditional crash rates reduced steeply from age 17–20 years through age 60–69 years. Adjusted crash risk instead peaked at age 20–29 years and decreased gradually until age 60–69 years. Additionally, elderly drivers had reduced crash involvement and fatality risks when using the adjusted crash risk compared to conventional crash rates. Finally, nighttime driving among
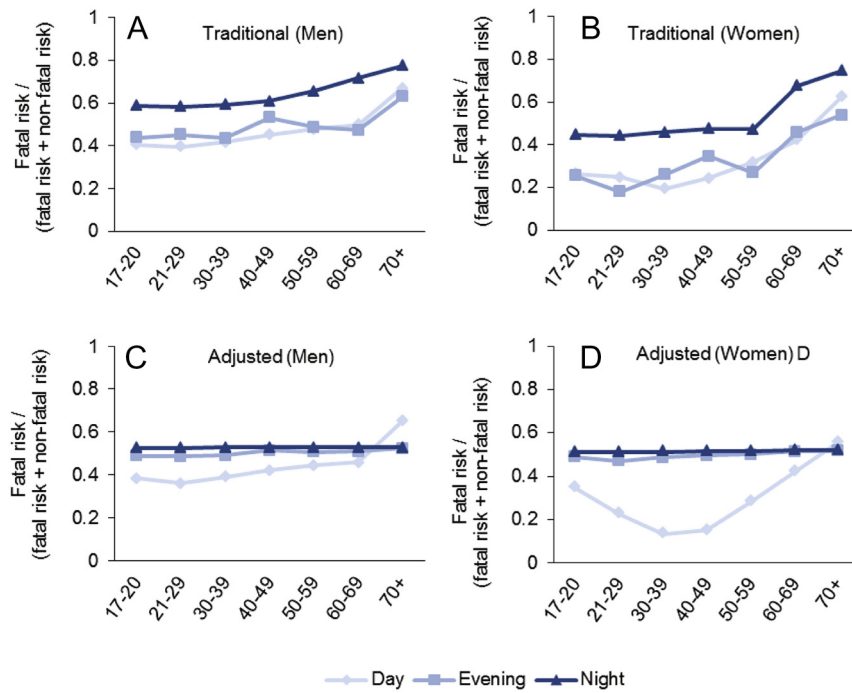
Fig. 5. Traditional and adjusted risk of fatal injury given multi-vehicle crash involvement by driver age and gender during daytime (06:00 h–18:00 h), evening (18:00 h–21:00 h), and nighttime (21:00 h–06:00 h) hours. Risk of fatal injury given crash involvement was calculated annually by dividing multi-vehicle fatal crash risk by the sum of multi-vehicle fatal and non-fatal crash risk.

teen drivers accounted for a smaller proportion of their single-vehicle crash risk than implied by crash rates.

The dramatic reduction in conventional crash rates from young to middle-age ranges reflects the common findings in the literature (e.g., Ma & Yan, 2014; McAndrews et al., 2013; Williams & Shabanova, 2003). However, the adjusted crash risks revealed a remarkably different age-trend in driver risk: Crash risk was highest among 21–29 year olds and thereon reduced gradually with age. The current results are in agreement with those obtained in studies using disaggregated models and quasi-induced exposure methods for crash risk analyses. These studies have shown that the youngest and oldest age groups are not the riskiest drivers. Rather, drivers in their 20s and 30s were those demonstrating the highest crash risk (Kam, 2003; Stamatiadis & Deacon, 1997). While the robustness of our findings is supported by previous reports, we do not argue here against the enforcement of driving restrictions targeting young drivers. Justification for road safety regulations would also depend on drivers' ability to recognize their own limitations and self-regulate their driving accordingly. The present investigation merely highlights that other age groups also exhibit substantial driver crash risk and may also benefit from targeted road safety initiatives.

Drivers, especially young males, are reported to have higher crash involvement rates at nighttime compared to daytime (e.g., Keall & Frith, 2006). Adjusting appropriately for the infrequency of nighttime travel, we discovered that crashes at night accounted for far less of the single-car crash risk of teen drivers compared to the traditional method. In Great Britain, young drivers are not restricted in their travel at night. Policymakers in countries where curfews are imposed on the youngest drivers (McCartt & Teoh, 2015) should be cognizant that the contribution of nighttime driving to single-vehicle crashes of teenagers may be exaggerated by traditional methods of analyzing crash risk.

Previous investigations using conventional crash rates have reported increased crash risk in older age (e.g., Cicchino & McCartt, 2014; Massie et al., 1995). We found that when controlling correctly for their small driver numbers and infrequent travel, crash involvement and fatality risks of elderly drivers were reduced. These findings are consistent with past research showing that older driver crash risk appears high

due to the biasing effects of their small driving exposure (Alvarez & Fierro, 2008; Antin et al., 2017; Fontaine, 2003; Hakamies-Blomqvist et al., 2002; Langford et al., 2006). Future research should include identification of age subgroups among older drivers given possible variation in their driving exposure and crash risks (Cicchino, 2015; Cicchino & McCartt, 2014).

Interestingly, our analysis revealed that among elderly drivers, the risk of sustaining a fatal injury from a crash remained constant across time of day. This finding lends support to the role of fragility in worsening injury outcomes for elderly drivers who are involved in crashes, since fragility (unlike crash seriousness) is not expected to be influenced by time of day. Therefore, countermeasures benefiting elderly drivers should focus on improving in-vehicle technology to reduce injury severity.

In either method, young and middle-aged drivers were more likely to sustain a fatal injury from a crash that occurred at night than during daytime. This resonates with previous research (e.g. Doherty et al., 1998). However, the adjusted method also revealed that fatal injury risk from nighttime crashes was similar to the risk from crashes in the evening. Thus, the current findings support the need to report age comparisons in crash involvement and injury severity by time of day and highlight the importance of accounting properly for the variability in travel exposure across time periods.

Findings from both methods regarding gender differences in crash risk were generally consistent with prior research; male drivers are more likely to be involved in fatal and non-fatal crashes compared to female drivers (e.g., Kim et al., 2008; Zhou et al., 2015). The adjusted method has also demonstrated that the fatal crash risk of women, particularly those in their 30s to 40s, was extremely low during daytime. These data fit prior travel behavior research showing that women, especially those with children, are more likely than men to make trips during daytime with the intention of serving passengers (e.g., Koppel, Charlton, Kopinathan, & Taranto, 2011; Rosenbloom, 2006). Although the presence of passengers is associated with in-vehicle distraction (Koppel et al., 2011; Stutts et al., 2005), having young passengers might be more protective than harmful by reducing risk-taking behaviors among women drivers. Future studies are needed to explore this possibility.

Our investigation has a number of potential limitations. First, motivated by concerns about the use of mileage in age comparisons of crash risk (Janke, 1991; Langford et al., 2013), we used annual trip numbers as our indicator of travel per person. In our study, traditional crash rates per trip produced the familiar pattern of excessive crash risk among the youngest drivers. Using different travel indicators might have resulted in smaller amount of risk exposure for older drivers and consequently larger crash rates in this age group. Nevertheless, previous studies have shown that reduction in travel associated with older age occurs both in terms of frequency of trips and distance traveled (Sivak & Schoettle, 2011). Second, we used self-reports of trips made, which may be associated with reporting biases that differ with driver age (e.g., Bricka & Bhat, 2006). Future studies may benefit from incorporating objective measures of risk exposure. Finally, we acknowledge that the new crash risk approach is based on an exposure metric that is more complex to compute in comparison to simple crash rate. Nevertheless, the new adjusted crash risk estimators are superior to the conventional crash rates in producing unbiased risk comparisons for driver groups and driving conditions that vary in their exposure to risk.

5. Conclusion

The current study applied a new approach to model crash risks based on exposure metric that bears a linear relation with crashes. Our findings draw attention to the invalidity of crash rates for risk comparisons among groups and conditions that vary in driving exposure. Specifically, we have demonstrated that conventional crash rates overestimate the actual risk of crash involvement and fatal injury for the youngest and oldest drivers as well as for nighttime driving. This work has important practical implications for improving road safety initiatives, as meaningful comparisons are essential for identifying truly at-risk drivers and driving conditions. It is hoped that the approach presented here will facilitate development of new crash modeling methodologies that are able to account for the non-linear shape of the safety performance function, and provide reliable crash risk estimates for road safety research and policies.

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