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Original article

Role of alcohol and marijuana use in the initiation of fatal two-vehicle crashes

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ABSTRACT

Purpose: To assess individual and joint effects of alcohol and marijuana on the initiation of fatal two-vehicle crashes.
Methods: Data on 14,742 culpable drivers (initiators) and 14,742 nonculpable drivers (noninitiators) involved in the same fatal two-vehicle crashes between 1993 and 2014 were obtained from the Fatality Analysis Reporting System. Multivariable conditional logistic regression models were used to assess the association of driver use of alcohol, marijuana, or both with fatal crash initiation with adjustment for demographic variables.
Results: Initiators were significantly more likely than non-initiators to test positive for alcohol (28.3% vs. 9.6%, $P < .0001$), marijuana (10.4% vs. 6.0%, $P < .0001$), and both substances (4.4% vs. 1.1%, $P < .0001$). Relative to drivers testing negative for both alcohol and marijuana, the adjusted odds ratios of fatal crash initiation were 5.37 (95% confidence interval [CI]: 4.88 to 5.92) for those testing positive for alcohol and negative for marijuana, 1.62 (95% CI: 1.43 to 1.84) for those testing positive for marijuana and negative for alcohol, and 6.39 (95% CI: 5.19 to 7.88) for those testing positive for both alcohol and marijuana.
Conclusions: Alcohol and marijuana each play a significant role in fatal crash initiation. When used in combination, alcohol and marijuana appear to have a positive interaction effect on the risk of fatal crash initiation on the additive scale.

Introduction

Drugged driving has become a serious public safety concern in the United States and in many other countries around the world [1–4]. Marijuana is the most commonly used nonalcohol drug in the general driver population and in drivers involved in crashes [5–13]. The prevalence of marijuana detected in fatally injured drivers in the United States increased from 4.2% in 1999 to 12.2% in 2010 [7]. Epidemiologic studies indicate that marijuana use, particularly in the last few hours or presence of delta-9-tetrahydrocannabinol in the blood, increases the risk of crash involvement and crash culpability [2,14–16]. Experimental studies have reported that marijuana use impairs psychomotor skills and driving performance [17,18]. Recent meta-analyses have confirmed that marijuana use is a significant risk factor for motor vehicle crashes although the extent to which the role marijuana plays in crash causation remains to be determined [2,19,20]. Concurrent use of alcohol and marijuana is the most frequently detected polydrug combination among drivers involved in fatal and nonfatal crashes [6,13].

As of November 9, 2016, 28 states and the District of Columbia have decriminalized marijuana for medical use and eight states have further decriminalized marijuana possession for recreational use among adults [21]. Among these, Washington and Colorado have experienced an increase in the proportion of drivers in fatal crashes who tested positive for marijuana since marijuana laws became effective [22,23]. Studies assessing the combined effects of alcohol and marijuana on crash involvement have produced different results with some indicating an additive effect [10,15,18,24–26], a likely synergistic effect [18,27–30], or no additive effect [16,31,32]. Experimental studies have mostly shown an additive effect and synergistic effect on cognitive performance at high concentrations of both marijuana and alcohol [17,18,32]. Inconsistent results are due in part to differences in study designs

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and exposure and outcome measures. For example, differences between comparison groups in spatiotemporal crash circumstances such as weather and road conditions may lead to biased risk estimates. In case-control studies, high refusal rates for drug testing in controls recruited through roadside surveys may introduce severe bias to the estimated odds ratios (ORs) [33]. By contrast, in pair-matched culpability or quasi-induced exposure studies, the two drivers in each pair are from the same two-vehicle crash [34,35]. Therefore, culpable drivers and nonculpable drivers are pair-matched on important tempospatial factors, such as weather and traffic conditions, making it possible to accurately estimate the crash initiation risk associated with alcohol and marijuana use. Although numerous studies have used the quasi-induced exposure design, few have evaluated joint effects of marijuana and alcohol on crash culpability based on pair-matched analysis [34]. In the present study, we performed a pair-matched analysis using data for drivers involved in fatal two-vehicle crashes to assess the individual and joint effects of alcohol and marijuana on crash initiation as determined by driving error that led to the crash.

Methods

Data

Data for this study came from the Fatality Analysis Reporting System (FARS) compiled by the National Center for Statistics and Analysis of the National Highway Traffic Safety Administration. The FARS database contains investigation data for all crashes that resulted in at least one fatality within 30 days and that occurred on public roads in the United States [36]. These data elements are acquired from police reports, medical records, state administrative files, and coroner reports. FARS includes driver characteristics (e.g., age, sex, alcohol, and drug test results, history of driving while intoxicated [DWI] conviction in the past 3 y), vehicle characteristics

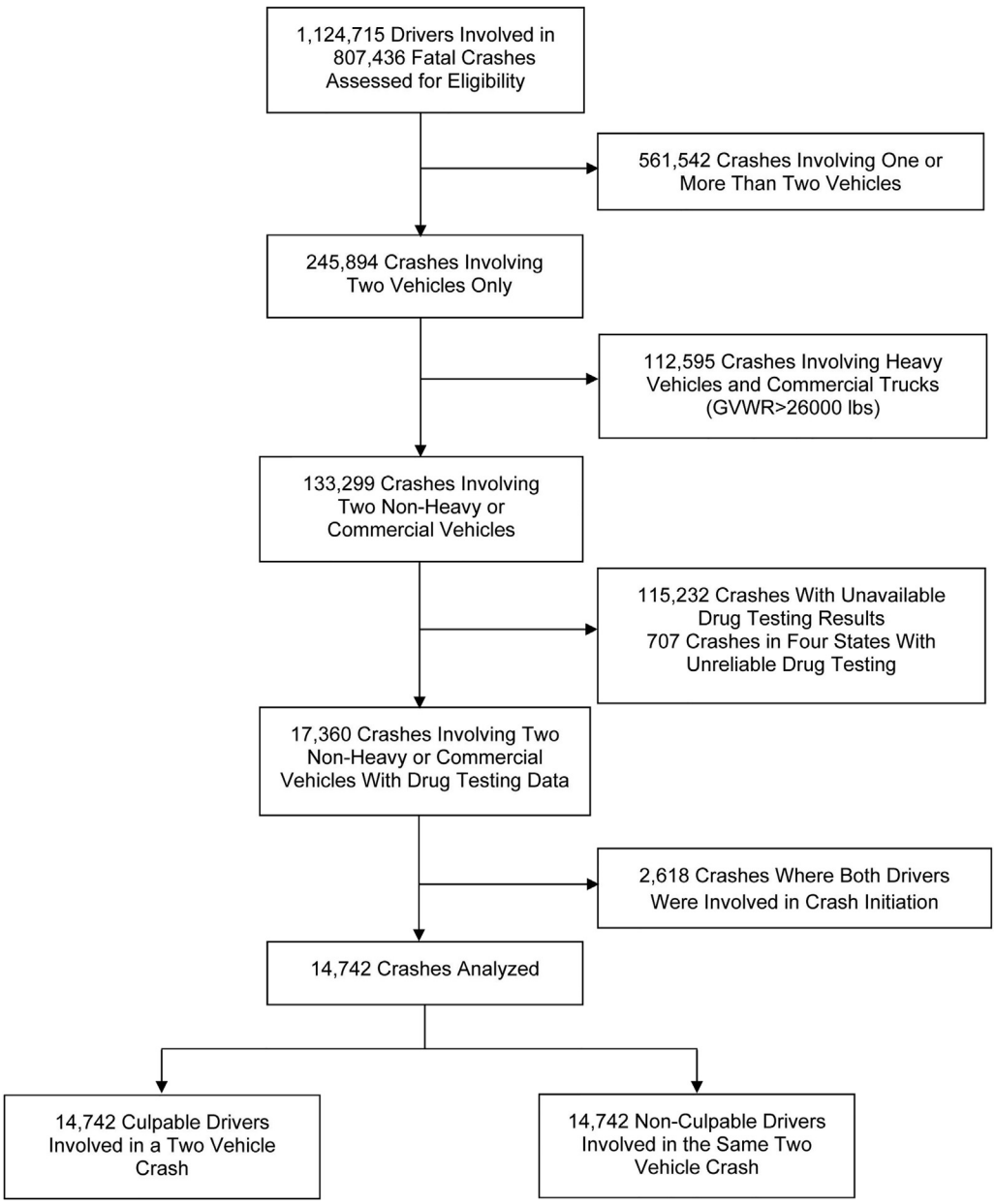

Fig. 1. Flow diagram of selection of drivers involved in two-vehicle crashes 1993–2014, Fatality Analysis Reporting System.

(e.g., make, model, body type, model y, gross vehicle weight rating, and vehicle configuration), and crash circumstances (e.g., crash location, date, time, roadway type, manner of collision, light conditions, and atmospheric conditions) [36]. Due to incomplete testing and reporting, toxicological testing results for nonalcohol drugs are only available for 30% of all fatally injured drivers nationwide. Twelve states performed drug testing on at least 80% of fatally injured drivers between 1 January 1993 and 31 December 2014.

This study was deemed exempt from review in accordance with title 45 of the Code of Federal Regulations part 46 by the Columbia University Medical Center Institutional Review Board (New York, NY).

Study design

A pair-matched analysis was used to assess the association between concurrent use of alcohol and marijuana and the risk of crash initiation in fatal two-vehicle crashes. Drivers who initiated the crashes due to driving errors (initiators), such as failure to stay in lane or yield right of way, were compared with drivers who were involved in the same crashes but were not culpable of initiating the crashes (noninitiators). The study sample consisted of drivers involved in fatal two-vehicle crashes in the United States between January 1, 1993 and December 31, 2014 in which drug testing results for both drivers involved in the same crash were recorded in the FARS. Excluded from the analysis were 561,542 crashes involving either single vehicles or more than two vehicles, 112,595 crashes involving a commercial truck or a heavy vehicle, 115,232 crashes where drug testing results were missing, and 2618 two-vehicle crashes in which both drivers were responsible for crash initiation (Fig. 1). Also excluded from the analysis were 707 two-vehicle crashes that occurred in Maryland, New Mexico, North Carolina, and Montana, because of concerns about the quality of drug testing data from these states [6].

Drug testing assessments

For each driver, FARS records toxicological testing data on up to three nonalcohol drugs. In cases where multiple nonalcohol drugs were detected, FARS records drugs in the following priority order: narcotics, depressants (exclusive of alcohol), stimulants, marijuana, and others [37]. Drug tests were conducted on blood and/or urine samples through liquid/gas chromatography, mass spectrometry, and radioimmunoassay techniques [9,37]. For drivers who tested positive for a drug and its metabolite, only the parent drug was recorded. Cannabinoids refer to the drug class for marijuana products such as hashish, pot, or weed [36]. Blood alcohol concentrations (BACs) were measured in grams per deciliter where a BAC of 0.01 g/dL or greater was considered alcohol-positive. Overall, 93.3% of all drivers studied had at least one drug test based on blood specimens.

Table 1
Frequency distribution of factors involved in crash initiation in 14,742 fatal two-vehicle crashes, Fatality Analysis Reporting System, 1993–2014

Type of driver error	No. (%)*
Failure to keep in proper lane	6340 (43.0)
Failure to yield right of way	3825 (22.3)
Driving too fast for conditions or in excess of posted maximum	3091 (21.0)
Failure to obey actual traffic signs, traffic control devices or traffic officers, failure to observe safety zone traffic laws	2226 (15.1)
Operating the vehicle in an erratic, reckless, careless or negligent manner, or at erratic or suddenly changing speeds	1201 (8.1)
Driving on wrong side of road	1142 (7.7)
Manslaughter or homicide or other assault	771 (5.2)
Making improper turn	462 (3.1)
Passing with insufficient distance or inadequate visibility or failing to yield to overtaking vehicle	369 (2.5)
Passing where prohibited	181 (1.2)
Any other	400 (2.7)

* The total exceeds 100% as more than one error is possible.

Statistical analysis

Frequency distribution of driving errors and other factors involved in initiating all crashes included in this study was computed. McNemar's test for pair-matched data was used to compare initiators and noninitiators by dichotomous driver characteristics (sex, DWI conviction in the past 3 y, crash within the past 3 y, speeding within the past 3 y, license suspension within the past 3 y, marijuana status, BAC, and survival status). Pearson's χ^2 test was used to compare the age categories. Associations of alcohol and marijuana use with the risk of crash initiation were measured by estimated ORs and 95 percent confidence intervals (95% CIs) obtained using conditional logistic regression modeling. Alcohol was assessed as a dichotomous variable and as a three-level categorical variable where BACs were divided into three groups: 0 g per dL, 0.01–0.07 g per dL, and ≥0.08 g per dL according to the current per se laws in the United States. The categorization allowed for analysis of the interaction of low levels of alcohol and marijuana. Interaction was assessed on the multiplicative and additive scales. Additive interaction was assessed based on three measures: the relative excess risk due to interaction [38,39], the attributable proportion due to interaction [40,41], and the synergy index [40,41].

To assess robustness of the study results, two separate sensitivity analyses were conducted by 1) restricting the analysis to drivers from the 12 states that tested more than 80% fatally injured drivers during the study period; and 2) splitting the study period into 1993–2003 and 2004–2014 to assess the possible impact of the increasing prevalence of marijuana use over time on the study results. Data analyses were performed using SAS, version 9.4, software (SAS Institute, Inc, Cary, North Carolina).

Results

From 1993 to 2014, there were 1,124,715 drivers involved in 807,436 fatal crashes in the United States. The analysis was based on data for 29,484 drivers (14,742 initiators and 14,742 noninitiators) involved in 14,742 fatal two-vehicle crashes. The three most common driving errors that led to these fatal crashes were failure to keep in proper lane (43%), failure to yield right of way (22%), and speeding (21%; Table 1).

Initiators were more likely than noninitiators to be under 35 years of age (52.7% vs. 38.0%; $P < .0001$), and to have had a crash (17.1% vs. 13.9%; $P < .0001$), a DWI conviction (4.5% vs. 1.7%; $P < .0001$), a speeding conviction (21.8% vs. 17.9%; $P < .0001$), and a license suspension (15.5% vs. 8.2%; $P < .0001$) within the previous three years (Table 2). Initiators were significantly more likely than noninitiators to test positive for alcohol (28.3% vs. 9.6%; $P < .0001$), marijuana (10.4% vs. 6.0%; $P < .0001$), and both alcohol and marijuana (4.2% vs. 1.1%; $P < .0001$; Table 2). Drivers who tested positive for alcohol, marijuana, or both were more likely than those who tested negative to be male, aged 25 to 44 years, and to have had a positive crash and violation history within the previous three years.

Multivariable conditional logistic regression models adjusted for driver age, sex, and driving history in the past three years. A scatterplot matrix did not show any patterns of multicolinearity among these variables. Relative to drivers who tested negative for both alcohol and marijuana, the estimated odds of fatal crash initiation

Table 2
Characteristics of drivers in fatal two-vehicle crashes by crash initiation status, Fatality Analysis Reporting System, 1993–2014

Driver characteristics*	Initiators (no. [%])	Noninitiators (no. [%])	*P* value
Age, y			
<25	4606 (31.2)	2567 (17.4)	<.0001
25–34	3163 (21.5)	3043 (20.6)	
35–44	2312 (15.7)	3048 (20.7)	
45–54	1727 (11.7)	2725 (18.5)	
55–64	1129 (7.7)	1918 (13.0)	
≥65	1805 (12.3)	1441 (9.8)	
Sex			
Female	4275 (29.0)	4254 (28.9)	.7760
Male	10,463 (71.0)	10,488 (71.1)	
Crash in the past 3 y			
Yes	2226 (17.1)	1816 (13.9)	<.0001
No	10,779 (82.9)	11,234 (86.1)	
DWI conviction in the past 3 y			
Yes	649 (4.5)	243 (1.7)	<.0001
No	13,913 (95.5)	14,361 (98.3)	
Speeding conviction in the past 3 y			
Yes	3176 (21.8)	2617 (17.9)	<.0001
No	11,386 (78.2)	11,987 (82.1)	
License suspension in the past 3 y			
Yes	2263 (15.5)	1193 (8.2)	<.0001
No	12,299 (84.5)	13,411 (91.8)	
Tested positive for alcohol (BAC, g/dL)			
≥0.01	4164 (28.3)	1419 (9.6)	<.0001
0.00	10,573 (71.7)	13,311 (90.4)	
Tested positive for marijuana			
Yes	1529 (10.4)	880 (6.0)	<.0001
No	13,213 (89.6)	13,862 (94.0)	
Survival status			
Died	7180 (48.7)	7155 (48.5)	.7708
Alive	7562 (51.3)	7587 (51.5)	

BAC = blood alcohol content, g/dL; DWI = driving while intoxicated.
* Data missing on sex for 4 drivers, on previous crashes for 3429 drivers, on license suspension for 318 drivers, on previous speeding conviction for 318 drivers, and on previous driving while impaired conviction for 318 drivers.

increased by more than fivefold for those testing positive for alcohol and negative for marijuana, 1.6 fold for those testing negative for alcohol and positive for marijuana, and over sixfold for those testing positive for both alcohol and marijuana (Table 3). The estimated ORs of fatal crash initiation increased with BAC level from 1.94 (95% CI: 1.69–2.24) for those testing negative for marijuana and positive for BAC level of 0.01–0.07 g per dL to 10.57 (95% CI: 7.96–14.05) for those testing positive for marijuana and BAC level of 0.08 g per dL or greater (Table 4). Positive interaction was present on the additive scale (relative excess risk due to interaction = 0.40 [95% CI: 0.04–0.76], attributable proportion due to interaction = 0.06, synergy index = 1.08). The estimated ORs for concurrent use of marijuana and alcohol (OR = 6.39) was less than the product of the estimated ORs associated with marijuana (OR = 1.62) and alcohol (OR = 5.37), indicating the presence of a negative

Table 3
Unadjusted and adjusted odds ratios for crash initiation of drivers in fatal two-vehicle crashes by marijuana and alcohol status, Fatality Analysis Reporting System, 1993–2014

Marijuana	Alcohol	Crude OR (95% CI)	Adjusted* OR (95% CI)
Negative	Negative	1.00 (Reference)	1.00 (Reference)
Positive	Negative	1.82 (1.63–2.03)	1.62 (1.43-1.84)
Negative	Positive	5.04 (4.62-5.49)	5.37 (4.88-5.92)
Positive	Positive	6.87 (5.67-8.33)	6.39 (5.19-7.88)

OR = odds ratio; CI = confidence interval.
* Model was adjusted for age, sex, and previous driving history within the past 3 y; crash, license suspension, driving while impaired conviction, and speeding conviction.

Table 4
Unadjusted and adjusted odds ratios for crash initiation of drivers in fatal two-vehicle crashes by marijuana and BAC level, Fatality Analysis Reporting System, 1993–2014

Marijuana	BAC, g/dL	Crude OR (95% CI)	Adjusted* OR (95% CI)
Negative	0	1.00 (Reference)	1.00 (Reference)
Positive	0	1.82 (1.63-2.03)	1.64 (1.44-1.86)
Negative	0.01–0.07	1.88 (1.66-2.14)	1.94 (1.69-2.24)
Positive	0.01–0.07	3.26 (2.41-4.40)	2.90 (2.09-4.03)
Negative	≥0.08	8.54 (7.62-9.56)	9.41 (8.29-10.67)
Positive	≥0.08	10.79 (8.29-14.04)	10.57 (7.96-14.05)

BAC = blood alcohol concentration; OR = odds ratio; CI = confidence interval.
* Model was adjusted for age, sex, and previous driving history within the past 3 y; crash, license suspension, driving while impaired conviction, and speeding conviction.

interaction on the multiplicative scale (Table 3). Similarly, a negative multiplicative interaction was present for each separate BAC level (Table 4).

Results from the sensitivity analysis based on data from states that tested at least 80% of all drivers involved in fatal crashes were consistent with results from the main analysis (Supplemental Tables 1 and 2). Similarly, results from the sensitivity analysis based on data for the two time periods (1993–2003 and 2004–2014) were similar (Supplemental Tables 3 and 4).

Discussion

Results of this study indicate that the risk of crash initiation from concurrent use of alcohol and marijuana among drivers may increase by more than fivefold when compared with drivers who test negative for alcohol and marijuana controlling for age, sex, and driving history within the previous 3 years. This study also confirms that use of marijuana alone increases crash culpability significantly, which is consistent with findings from previous meta-analyses [2,19,20], and experimental [42–45] and case-control studies [37,46,47]. As expected, the risk of fatal crash initiation increased substantially with BAC levels.

Findings from previous culpability studies are inconsistent; some reported elevated crash culpability associated with marijuana [48,49], whereas others found no evidence of increased crash culpability associated with marijuana alone [26,50–52]. Several factors may explain the conflicting results, including methodological problems, such as differences in types of specimens used for drug testing, study designs, and study populations [26,51,53]. Based on a large sample size and pair-matched analysis, the present study confirms that marijuana use is associated with a 62% increased risk of fatal crash initiation in the absence of alcohol when adjusting for age, sex, driving history, and crash circumstances. Furthermore, this study provides compelling epidemiological evidence that there exists a positive interaction effect of alcohol and marijuana on the risk of fatal crash initiation on the additive scale, and a negative interaction on the multiplicative scale.

In the past two decades, the prevalence of marijuana detected in fatally injured drivers has increased markedly [7]. During the same time period, 28 states and the District of Columbia have enacted legislation to decriminalize marijuana for medical use, including eight states that have further decriminalized possession of small amounts for adult recreational use [21]. Hence it is important to understand the relationship between marijuana use and driving safety through rigorously designed studies [34]. In the present study, the two drivers in each fatal two-vehicle crash were exposed to the same traffic conditions, such as environment, weather, and time and day of the crash, thereby eliminating the

bias of major confounding factors that may arise in alternative study designs.

This study has several notable limitations. The positivity of marijuana in drug testing indicates marijuana use but not necessarily marijuana-induced impairment at the time of crash [4]. In addition, toxicological testing methods and specimens may vary across states and jurisdictions. However, variations in testing specimens or methods across states and jurisdictions are unlikely to have any significant impact on the internal validity of the study findings because initiators and noninitiators were pair matched, and because more than 93% of study subjects had at least one blood test. Finally, the elevated risk of fatal crash initiation associated with marijuana use might be explained to some degree by residual bias from unmeasured confounding factors, such as health status and comorbidities. It is possible that some drivers tested positive for marijuana because they were using marijuana for permissible medical conditions that may adversely affect psychomotor and sensory functions necessary for safe driving.

Conclusions

Alcohol and marijuana each play a significant role in fatal crash initiation. Concurrent use of alcohol and marijuana appears to have a positive interaction effect on the risk of fatal crash initiation on the additive scale but not on the multiplicative scale. Our results suggest that countermeasures targeting both alcohol-impaired driving and drugged driving are needed to improve traffic safety. As the prevalence of marijuana use in drivers continues to rise, it is urgent to understand the role of marijuana in motor vehicle crashes and injuries when used in isolation and in combination with alcohol and other drugs. Future research should determine the dose-response effects of marijuana on crash risk, crash culpability, and injury outcomes.

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Guohua Li as the corresponding author had full access to all of the data in the study and takes full responsibility for the integrity of the data and the accuracy of the data analysis. All authors have participated in the drafting of the work and/or in the critical revision of the intellectual content of the work and provided final approval of the submitted version and agreed to be accountable for all aspects of the work. All the authors made substantial contributions to study design or acquisition of data, or statistical analysis or analysis and interpretation of data:

Guohua Li is involved in the study concept and design and takes responsibility of obtained funding and study supervision. Acquisition of data is done by Guohua Li and Joanne E. Brady, whereas the statistical analysis was done by Stanford Chihuri, Joanne E. Brady. Analysis and interpretation of data, drafting of manuscript, and critical revision of the manuscript for important intellectual content was done by all the authors.

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Appendix

Supplemental Table 1
Unadjusted and adjusted odds ratios for crash initiation of drivers in fatal two-vehicle crashes by marijuana and alcohol status in states that tested ≥80% fatally injured drivers, Fatality Analysis Reporting System, 1993–2014

Marijuana	Alcohol	Crude OR (95% CI)	Adjusted* OR (95% CI)
Negative	Negative	1.00 (Reference)	1.00 (Reference)
Positive	Negative	2.09 (1.70–2.59)	1.73 (1.37–2.17)
Negative	Positive	4.98 (4.23–5.86)	5.07 (4.24–6.06)
Positive	Positive	7.68 (5.41–10.90)	7.04 (4.84–10.25)

OR = odds ratio; CI = confidence interval.
* Adjusted for age, sex, previous driving history within the past 3 years; crash, license suspension, driving while impaired conviction, and speeding conviction.

Supplemental Table 2
Unadjusted and adjusted odds ratios for crash initiation of drivers in fatal two-vehicle crashes by marijuana and BAC level in states that tested ≥80% fatally injured drivers, Fatality Analysis Reporting System, 1993–2014

Marijuana	BAC, g/dL	Crude OR (95% CI)	Adjusted* OR (95% CI)
Negative	0	1.00 (Reference)	1.00 (Reference)
Positive	0	2.09 (1.70-2.59)	1.75 (1.39-2.21)
Negative	0.01–0.07	1.76 (1.38-2.24)	1.76 (1.36-2.28)
Positive	0.01–0.07	3.00 (1.74-5.18)	2.76 (1.53-4.99)
Negative	≥0.08	8.54 (6.90–10.56)	9.16 (7.27–11.55)
Positive	≥0.08	13.34 (8.17–21.77)	12.54 (7.46–21.09)

BAC = blood alcohol content, g/dL; OR = odds ratio; CI = confidence interval.
* Adjusted for age, sex, previous driving history within the past 3 years; crash, license suspension, driving while impaired conviction, and speeding conviction.

Supplemental Table 3
Adjusted odds ratios for crash initiation of drivers in fatal two-vehicle crashes by marijuana and alcohol status, Fatality Analysis Reporting System; 1993–2003 and 2004–2014

Marijuana	Alcohol	1993–2003	2004–2014
		Adjusted* OR (95% CI)	Adjusted* OR (95% CI)
Negative	Negative	1.00 (Reference)	1.00 (Reference)
Positive	Negative	1.41 (1.14-1.74)	1.72 (1.47-2.02)
Negative	Positive	5.42 (4.70-6.25)	5.37 (4.70-6.14)
Positive	Positive	5.59 (4.02-7.79)	6.97 (5.31-9.14)

OR = odds ratio; CI = confidence interval.
* Adjusted for age, sex, and previous driving history within the past 3 years; crash, license suspension, driving while impaired conviction, and speeding conviction.

Supplemental Table 4
Adjusted odds ratios for crash initiation of drivers in fatal two-vehicle crashes by marijuana and BAC level, Fatality Analysis Reporting System; 1993–2003 and 2004–2014

Marijuana	BAC, g/dL	1993–2003	2004–2014
		Adjusted* OR (95% CI)	Adjusted* OR (95% CI)
Negative	0	1.00 (Reference)	1.00 (Reference)
Positive	0	1.44 (1.17-1.79)	1.73 (1.48-2.04)
Negative	0.01–0.07	2.12 (1.73-2.60)	1.79 (1.47-2.18)
Positive	0.01–0.07	2.38 (1.38-4.10)	3.28 (2.17-4.94)
Negative	≥0.08	9.14 (7.61-10.97)	9.75 (8.19-11.62)
Positive	≥0.08	8.62 (5.59-13.27)	12.22 (8.36-17.84)

BAC = blood alcohol content, g/dL; OR = odds ratio; CI = confidence interval.
* Adjusted for age, sex, and previous driving history within the past 3 years; crash, license suspension, driving while impaired conviction, and speeding conviction.