



# Fatal crashes in the 5 years after recreational marijuana legalization in Colorado and Washington

Jayson D. Aydelotte<sup>a</sup>, Alexandra L. Mardock<sup>b</sup>, Christine A. Mancheski<sup>c</sup>, Shariq M. Quamar<sup>d</sup>, Pedro G. Teixeira<sup>a</sup>, Carlos V.R. Brown<sup>a</sup>, Lawrence H. Brown<sup>c,\*</sup>

<sup>a</sup> Division of Acute Care Surgery, Department of Surgery and Perioperative Care, Dell Medical School at the University of Texas Austin, 1500 Red River St., Austin, TX 78701, USA

<sup>b</sup> UCLA David Geffen School of Medicine, 10833 Le Conte Ave, Los Angeles, CA 90095, USA

<sup>c</sup> Division of Emergency Medicine, Department of Surgery and Perioperative Care, Dell Medical School at the University of Texas Austin, 1400 N IH35, Suite 2.230, Austin, TX 78701, USA

<sup>d</sup> University of Texas, c/o Division of Emergency Medicine, 1400 N IH35, Suite 2.230, Austin, TX 78701, USA

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## ABSTRACT

Colorado and Washington legalized recreational marijuana in 2012, but the effects of legalization on motor vehicle crashes remains unknown. Using Fatality Analysis Reporting System data, we performed difference-in-differences (DD) analyses comparing changes in fatal crash rates in Washington, Colorado and nine control states with stable anti-marijuana laws or medical marijuana laws over the five years before and after recreational marijuana legalization. In separate analyses, we evaluated fatal crash rates before and after commercial marijuana dispensaries began operating in 2014. In the five years after legalization, fatal crash rates increased more in Colorado and Washington than would be expected had they continued to parallel crash rates in the control states (+1.2 crashes/billion vehicle miles traveled, CI: -0.6 to 2.1,  $p = 0.087$ ), but not significantly so. The effect was more pronounced and statistically significant after the opening of commercial dispensaries (+1.8 crashes/billion vehicle miles traveled, CI: +0.4 to +3.7,  $p = 0.020$ ). These data provide evidence of the need for policy strategies to mitigate increasing crash risks as more states legalize recreational marijuana.

## 1. Introduction

Colorado and Washington became the first two U.S. states to enact recreational marijuana legalization in late 2012; the first commercial dispensaries began opening in 2014. Since then, eight additional states and Washington, D.C. have also legalized recreational marijuana. These laws have raised concerns about the potential for increased use of marijuana and other illicit substances, an increased burden on the health care system, and higher rates of intoxication-related motor vehicle crashes and fatalities (White House Office of National Drug Control Policy, 2014; Ghosh et al., 2015; Wilkinson et al., 2016).

### 1.1. Marijuana legalization and marijuana use

Data on the relationship between marijuana legalization and marijuana use are mixed. Two studies have found no difference in marijuana use among teenagers in non-marijuana and medical marijuana states (Anderson et al., 2015; Schmidt et al., 2019) and another found

no association between recreational marijuana legalization and increased marijuana use among college students in Colorado (Jones et al., 2018). Two other studies reported increased marijuana use among adults in states that adopted medical marijuana laws (Wen et al., 2015; Mauro et al., 2019), and another reported increased marijuana use among college students after recreational marijuana legalization in Washington (Miller et al., 2017). Reported indirect indicators of increased marijuana use after either medical or recreational legalization include increased marijuana-related arrests (Chu, 2014; Ellison and Spohn, 2017), increased marijuana-related rehabilitation admissions (Chu, 2014) and changes in students' time commitment to scholarly vs. leisure activities (Chu and Gershenson, 2018).

The data are also mixed for whether marijuana legalization influences the use of other drugs. Hospital admissions related to "hard drugs" increased after decriminalization of marijuana in the Lambeth borough of London (Kelly and Rasul, 2014). An analysis of 2013–2014 National Survey of Drug Use and Health data found adolescents aged 12–18 years were more likely to use cocaine, crack and heroin if they lived in

\* Corresponding author at: Division of Emergency Medicine, Dell Medical School, 1400 N IH35, Suite 2.230, Austin, TX 78701, USA.

E-mail address: [lhbrown@ascension.org](mailto:lhbrown@ascension.org) (L.H. Brown).

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medical marijuana states, although there were no differences in use of hallucinogens, inhalants, pain relievers, sedatives or stimulants (Wong and Lin, 2019). To the contrary, Shi et al. (2019) found no increase in prescriptions for Schedule II and Schedule III opioids among Medicaid beneficiaries in states that legalized recreational marijuana; in fact, there was some evidence suggesting recreational marijuana legalization led to fewer Schedule III opioid prescriptions in Alaska, Oregon and Washington DC.

### 1.2. Effects of marijuana legalization on the health care system

Data regarding the effects of marijuana legalization on the health care system are more consistent. Marijuana-related emergency department visits increased following recreational marijuana legalization in Colorado, at least partly due to "marijuana tourists" visiting from other states (Kim and Monte, 2016; Kim et al., 2016). At one Washington tertiary pediatric hospital, unintentional marijuana exposures in children under 7 years of age increased from 1.2 to 3.9 events per year after recreational marijuana legalization (Thomas et al., 2018). At a Colorado tertiary children's hospital, marijuana-related urgent care and emergency department visits—including behavioral health consultations—among 13- to 21- year-olds increased steadily from 2005 through 2015 (Wang et al., 2018). A similar trend was seen at the institution's "safety net" general hospital, with an abrupt significant increase in marijuana-related visits among patients aged 15 years and greater following recreational marijuana legalization (Calcaterra et al., 2018).

### 1.3. Marijuana use and driving risks

Marijuana use increases driving risks (Li et al., 2012). Marijuana use affects attention, slows reaction times, decreases motor skills, increases "lateral position deviation"—lane weaving—and results in generally slower driving (Crancer et al., 1969; Ramaekers et al., 2000; Riedel and Davies, 2005; Ronen et al., 2010; Hartman and Huestis, 2013; Hartman et al., 2015). All of these can contribute to a higher risk of collisions. A study using data from the U.S. Fatality Analysis Reporting System (FARS) found approximately 5% of drivers in investigated fatal crashes were under the influence of marijuana (alone, not combined with alcohol) at the time of the crash, and that marijuana use was associated with the driver having taken unsafe actions that led to the crash (Bédard et al., 2007). There appears to be a dose-response relationship in this phenomenon, with higher levels of tetrahydrocannabinol (THC) being associated with more frequent unsafe actions that lead to crashes (Ramaekers et al., 2004; Dubois et al., 2015).

### 1.4. Marijuana legalization and motor vehicle crashes

Whether marijuana legalization leads to increased numbers of fatal motor vehicle crashes is less clear. The prevalence of detected THC among drivers in fatal crashes increased following legalization of medical marijuana in some states (Masten and Guenzburger, 2014; Salomonsen-Sautel et al., 2014; Steineman et al., 2018; Sevigny, 2018), although there was no effect in other medical marijuana states (Masten & Guenzburger, 2014; Sevigny, 2018). Two studies, however, have reported aggregate decreases in population-based traffic fatality rates after legalization of medical marijuana (Anderson et al., 2013; Santaella-Tenorio et al., 2017), although again the effects varied widely across individual states. Decreases in crash fatality rates after medical marijuana legalization might seem counter-intuitive, but some studies have suggested that marijuana is a substitute for alcohol and that marijuana legalization leads to decreased alcohol use and thus fewer alcohol-related crashes (DiNardo and Lemieux, 2001; Anderson and Rees, 2014; Anderson et al., 2015; Hansen et al., 2018a). On the other hand, one study has suggested binge drinking is a complement to increased marijuana consumption among adults in medical marijuana

states (Miller et al., 2017), and another found no relationship between recreational marijuana legalization and changes in alcohol consumption among college students in Washington (Wen et al., 2015).

To date, three studies have specifically examined the effect of recreational marijuana legalization on traffic crashes. Aydelotte et al. (2017) conducted a difference-in-differences analysis evaluating crashes in Colorado and Washington in the first three years following recreational marijuana legalization, finding no significant increase in total crashes, fatal crashes or numbers of fatalities per billion vehicle miles traveled (BVMT) when compared with similar states without medical marijuana laws. Using interrupted time series techniques, Lane and Hall (2019) found an immediate step increase (i.e., change in y intercept) in population-based crash fatality rates after recreational marijuana legalization in Colorado; for Washington they found an immediate step increase in crash fatalities followed by a trend reduction (i.e., change in slope). They found no significant changes in population-based crash fatality rates in Oregon. Hansen et al. (2018b) used synthetic control techniques to compare evolutions in crash fatalities after the 2014 opening of commercial marijuana dispensaries in Colorado and Washington with synthetic counterfactuals based on data for 20 other states. They found no significant increase in fatalities per BVMT in either Colorado or Washington in the first two years after commercial dispensaries opened.

### 1.5. Study purpose and hypothesis

This study builds on those previous works. We used a difference-in-differences approach to evaluate changes in fatal crash rates in Colorado and Washington following recreational marijuana legalization over a longer (five-year) post-legalization timeframe. We used BVMT as the unit of exposure, and included as controls only those states with stable anti-marijuana or medical marijuana status throughout the study period. We first evaluated the effect of legalization at the end of 2012; we then considered the effect of commercial dispensaries opening in 2014. Our null hypothesis was that changes in fatal crash rates in Colorado and Washington following recreational marijuana legalization would not differ from contemporaneous changes seen in the control states.

## 2. Methods

### 2.1. Design

This was a retrospective, longitudinal cohort study of fatal crashes reported in the FARS database from November 2007 through December 2017—encompassing the 60 months immediately before and after recreational marijuana legalization in Colorado and Washington. FARS is a nationwide census of fatal crashes: Any crash involving a motor vehicle traveling on a trafficway customarily open to the public that results in the death of a motorist or a non-motorist within 30 days is eligible for inclusion in the database (National Highway Traffic Safety Administration, 2018).

### 2.2. Exposure

The 2012 passage of recreational marijuana laws in Colorado and Washington was the exposure of interest. We compared pre- and post-legalization fatal crashes occurring in Colorado and Washington with those occurring in the nine U.S. states that either (a) had existing medical marijuana laws and did not adopt recreational marijuana laws during the study period (Hawaii, Montana, New Mexico, Rhode Island, Vermont); or (b) had anti-marijuana laws and did not adopt medical or recreational marijuana laws during the study period (Idaho, Kansas, Nebraska, South Dakota) (National Conference of State Legislatures, 2019). Given the evidence that both decriminalization of marijuana and medical marijuana legalization lead to increased marijuana use in at

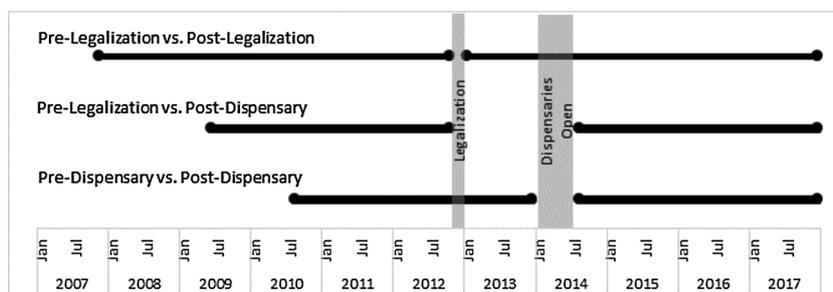


Fig. 1. Study periods evaluated.

least some settings (Chu, 2014; Wen et al., 2015; Mauro et al., 2019), we chose to isolate the effects of recreational marijuana legalization by purposefully selecting control states that maintained their medical marijuana or anti-marijuana status throughout the study period.

Legalization of recreational marijuana was not an instantaneous event: The first commercial marijuana dispensaries did not open until January 2014 in Colorado, and July 2014 in Washington. We therefore considered three balanced implementation timelines in our analysis (see Fig. 1). First, we treated legalization as a near-immediate event and compared fatal crash rates in the 60 months before (November 2007 – October 2012) and after (January 2013 – December 2017) legalization, excluding the months of November 2012 (legalization in Colorado) and December 2012 (legalization in Washington). Second, we repeated the analysis comparing fatal crash rates in only the 41 months after commercial dispensaries were operating in both Colorado and Washington (August 2014 – December 2017) with fatal crash rates in the final 41 months of the pre-legalization period (June 2009 – October 2012). Lastly, we compared fatal crash rates in the 41-month post-dispensary period with fatal crash rates in the 41 months immediately preceding the opening of the first commercial dispensaries (August 2010 – December 2013).

### 2.3. Outcomes

Our primary outcome measure was monthly fatal crash rates, measured as fatal crashes per BVMT. The number of fatal crashes for each included state and month was extracted from the FARS annual "accident" files (National Highway Traffic Safety Administration, 2019). The number of vehicle miles traveled for each state and month was obtained from Federal Highway Administration (FHWA) *Traffic Volume Trends* reports (Federal Highway Administration, 2007-2017).

### 2.4. Covariates

We considered several state-level population, economic, roadway and traffic factors that might differ among Colorado, Washington and the control states and thus potentially confound any association between recreational marijuana laws and fatal crashes. Population density was based on annual population and geographic land area estimates from the U.S. Census Bureau (2019a,2019b,2019c). State annual per capita gross domestic product (GDP) was calculated using U.S. Federal Reserve Bank (2019) GDP data. State seatbelt laws were categorized as primary or secondary based on U.S. Governors' Highway Safety Association (2019a). Whether and when states had enacted a "texting and driving" ban was determined from an Insurance Institute for Highway Safety report (McCartt et al., 2014) and by searching individual state legislative databases. Traffic density was calculated as vehicle miles traveled per lane mile of roadway, obtained from the Federal Highway Administration's (2019a) annual *Highway Statistics* publication (Table HM-20). Annual state revenues used for highways (e.g., construction, maintenance and repair) was also obtained from the *Highway Statistics* publication (Table SF-1) (Federal Highway Administration, 2019b). Both GDP and expenditures on highways were

adjusted to year 2012 dollars using consumer price index (CPI) data (Bureau of Labor Statistics, 2019). Whether control states were contiguous to Colorado or Washington, and whether they were medical marijuana states or anti-marijuana states, were also included in the models.

### 2.5. Statistical methods

We conducted difference-in-differences analyses (Dimick and Ryan, 2014) comparing post-legalization vs. pre-legalization changes in outcome measures in Colorado and Washington with those observed in the control states. All analyses were conducted in Stata MP (Version 15.1, StataCorp, College Station, TX).

First, we confirmed parallel trends for the pre-legalization fatal crash rates by graphing and inspecting the data. We then used regression modeling for longitudinal panel data (Stata: xtreg) (Anonymous, 2019a) to model crashes per BVMT as a function of recreational marijuana legalization, controlling for both state- and time-level fixed effects and the identified covariates (Twisk, 2013; Dimick and Ryan, 2014). The statistical model was:

$$Y_{st} = \beta_0 + \beta_1 RML_{st} + \beta_2 X_{st} \dots \beta_n X_{st} + \delta_s + \gamma_t + \epsilon_{st}$$

Where  $Y_{st}$  is the outcome measure in state  $s$  at time  $t$ ;  $RML_{st}$  is recreational marijuana legalization status in state  $s$  at time  $t$ ;  $X$  represents the array of covariates;  $\delta$  represents state fixed effects;  $\gamma$  represents time fixed effects, and  $\epsilon$  is the error term. Due to the small number of intervention states ( $N = 2$ ), we conducted the analyses incorporating bootstrap standard errors, which does not assume normal distribution of the model residuals and enables the calculation of bias-corrected confidence intervals (Mooney and Duval, 1993; Haukoos and Lewis, 2005; Anonymous, 2019b).

As this was an observational study of existing data, there was no *a priori* sample size determination.

### 2.6. Ethical review

The University of Texas-Austin Institutional Review Board administratively affirmed that this analysis did not constitute human subjects research.

## 3. Results

Table 1 summarizes the population, economic, roadway and traffic characteristics of the included states (Appendix Table A1 includes detailed data for each state). The control states were generally smaller and more urban, but the aggregate characteristics of the exposure and control states were similar.

From November 2007 through December 2017 there were 25,561 fatal crashes in Colorado, Washington and the nine control states; 12,348 crashes occurred in the pre-legalization period and 12,865 occurred in the post-legalization period.

**Table 1**

Baseline (2007) population, economic, roadway and traffic characteristics of the included states. BVMT = billion vehicle miles traveled; GDP = gross domestic product; Highway Funding = state revenues used for highways.

	Colorado & Washington	Control States
BVMT, median (IQR)	49.2 (45.6-57.6)	19.2 (9.6-31.2)
BVMT, Total	101.9	133.4
GDP, median (IQR) (\$ billion)	296.0 (246.0-346.0)	65.2 (47.9-122.5)
GDP, Total (\$ billion)	592	549
Per Capita GDP, median (IQR) (\$ 1000)	57.8 (56.3-59.3)	48.2 (43.9-50.1)
Population, median (IQR) (million)	5.7 (4.8-6.5)	1.8 (1.1-2.8)
Population, Total (million)	11.3	12.9
Population Density (people / mi <sup>2</sup> )	72.0 (46.7-97.3)	64.8 (18.1-120.1)
1" / 2" Seatbelt Law	1 / 1	5 / 4
Lane Miles, median (IQR)	85.8 (83.4-88.2)	68.3 (31.3-93.4)
Lane Miles, Total	171.6	532.5
Traffic Density, median (IQR) (1000 VMT / Lane Mile)	574.8 (523.2-691.2)	464.4 (217.2-763.2)
Highway Funding, median (IQR) (\$ billion)	2.9 (2.5-3.3)	0.8 (0.5-2.0)
Highway Funding, Total (\$ billion)	69.2	81.4
Highway Funding / Lane Mile (\$ 1000), median (IQR)	33.8 (27.9-39.6)	16.1 (10.7-27.4)

3.1. Primary outcomes: crash rates

Fig. 2 shows the fatal crash rates in Colorado and Washington vs. the control states for both the pre- and post-legalization time periods. The crash rates are displayed annually for clarity, and shown with overlapping y intercepts. Although pre-legalization fatal crash rates were consistently higher in the control states (right-hand axis), the pre-legalization trends were similar. In the post-legalization and post-dispensary periods, the trend lines clearly diverge.

Table 2 summarizes the results of the multi-variable difference-in-differences analyses. Post-legalization crash rates in Colorado and Washington were higher—but not significantly so—than would be expected had they continued to parallel those of the control states (DD: +1.2; CI: -0.6 to +2.1; p = 0.087). The effect became stronger and statistically significant when focusing on the post-dispensary period. This was true whether comparing the post-dispensary period to the pre-legalization period (DD: +1.8; CI: +0.4 to + 3.7; p = 0.020) or to the immediate pre-dispensary period (DD: +1.6; CI: +0.7 to +3.4; p = 0.026). (Detailed regression models are shown in Appendix Table A2–A4.)

4. Discussion

In this study we found increased fatal crash rates in the five years following recreational marijuana legalization in Colorado and Washington. The overall effect (+1.2 fatal crashes/BVMT) was not statistically significant, with a bias corrected confidence interval of -0.6

to +2.1. The effect in the post-dispensary period, however, was more pronounced, statistically significant, and persisted regardless of the baseline comparison period. What remains unclear is whether the post-dispensary effect is specific to the opening of commercial dispensaries, or a cumulative effect of increasing post-legalization follow-up time.

These findings complement those of previous analyses. Although their findings also did not reach statistical significance, Aydelotte et al (2017) did report higher fatal crash rates in Colorado and Washington in the first three years after recreational marijuana legalization. The effect size in that study (+0.2 fatalities/BVMT, CI: -1.4, +0.9) was small, but the practical implication was estimated to be as many as 77 additional deaths over the study period. The difference between the post-legalization point estimates in Aydelotte's and our results might be attributable to the longer follow-up time or to differences in methodology. The previous study included only non-medical marijuana control states and did not adjust for the same population, economic, roadway and traffic factors included in this analysis.

Lane and Hall (2019) found a significant immediate step increase of +0.8 crash fatalities per million population after legalization in Colorado, and for Washington they found an significant immediate step increase of +0.9 crash fatalities per million population. Their sensitivity analysis incorporating a six-month lag to allow for the delay in the opening of commercial dispensaries produced results similar to those of their primary analysis. Importantly, however, dispensaries did not actually begin operating until 12 months after recreational marijuana legalization in Colorado, and 18 months after legalization in Washington. We found stronger post-dispensary effects when isolating

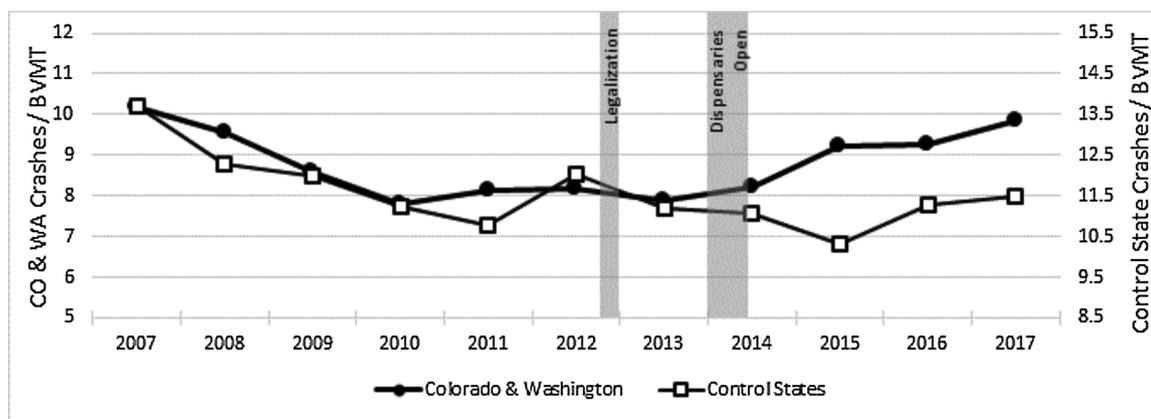


Fig. 2. Annual fatal crash rates in Colorado, Washington and the controls states, 2007-2017. Colorado (CO) and Washington (WA) fatal crash rates are indexed on the left-hand axis; control state fatal crash rates are indexed on the right-hand axis. BVMT = billion vehicle miles traveled.

**Table 2**

Results of the difference-in-differences analyses. RML = recreational marijuana legalization; No-ML = no marijuana legalization; MML = medical marijuana legalization; Diff. = difference; DD = difference-in-differences; CI = bias-corrected confidence interval; Sig. = significance.

	RML States			Control States			Crude DD	Adjusted DD (95% CI)	Sig.
	Before	After	Diff.	Before	After	Diff.			
<b>Fatal Crashes/BVMT</b>									
Pre- vs. Post-Legalization	8.5	8.9	+0.4	11.8	11.1	-0.7	+1.1	+1.2 (-0.6 to 2.1)	0.087
Pre-Legalization vs. Post-Dispensary	8.2	9.3	+1.1	11.6	11.1	-0.5	+1.6	+1.8 (+0.4 to +3.7)	0.020
Pre- vs. Post-Dispensary	8.2	9.3	+1.1	11.3	11.1	-0.2	+1.3	+1.6 (+0.7 to +3.4)	0.026

the actual post-dispensary period.

Hansen et al. (2018b) reported non-significant changes in crash fatality rates in Colorado and Washington from 2014 (the year commercial dispensaries began opening) through 2016. Again, however, the overall effect was upward: +0.4 additional fatalities per BVMT in CO and + 0.7 additional fatalities per BVMT in WA. That study included all of 2013—the first year of recreational marijuana legalization—in its baseline period for developing the synthetic controls, and included all of 2014 in its post-dispensary period even though dispensaries did not open in Washington until mid-2014. Again, we found stronger post-dispensary effects when isolating the actual pre- and post-dispensary periods.

While analyses using large datasets risk achieving statistically significant results with questionable clinical or practical significance, that is not the case here. Multiplying the lower bound of the 95% confidence interval for the post-dispensary effect by the approximately 115 BVMT that occur in Colorado and Washington each year suggests a minimum estimate of 46 additional fatal crashes annually.

We analyzed the aggregate effects of recreational marijuana legalization in Colorado and Washington compared with the control states, but the effects in Colorado and Washington could differ from each other. Indeed, a post-hoc analysis revealed the effects in Colorado were consistently stronger than those in Washington (see Table 3). Also, individual localities within both states can adopt local ordinances regulating or prohibiting marijuana sales, (Dilley et al., 2017) so any effects of recreational marijuana legalization might not be uniform throughout a state. Future research exploring within-state differences in the effects of recreational marijuana legalization on individual counties would be valuable.

A unique aspect of our analysis was our choice of control states. States are remarkably heterogenous, and there is no established mechanism for selecting comparative control states for marijuana policy studies. We chose to isolate the effects of recreational marijuana legalization by purposefully selecting control states that maintained their

**Table 3**

Post-hoc analysis of difference-in-differences for Colorado and Washington separately. RML = recreational marijuana legalization; Diff. = difference; DD = difference-in-differences.

	RML States			Control States			Crude DD
	Before	After	Diff.	Before	After	Diff.	
<b>Fatal Crashes/BVMT</b>							
Pre- vs. Post-Legalization							
Colorado Only	9.2	10.0	+0.8	11.8	11.1	-0.7	+1.5
Washington Only	7.9	8.0	+0.1				+0.8
Pre-Legalization vs. Post-Dispensary							
Colorado Only	9.0	10.4	+1.4	11.6	11.1	-0.5	+1.9
Washington Only	7.6	8.4	+0.8				+1.3
Pre- vs. Post-Dispensary							
Colorado Only	9.1	10.4	+1.3	11.3	11.1	-0.2	+1.5
Washington Only	7.3	8.4	+1.1				+1.3

medical marijuana or anti-marijuana status throughout the study period. Of course, state laws are dynamic and the specific details of any individual state's marijuana statutes (e.g., penalties for possession; conditions approved for medical treatment; establishment of medical marijuana dispensaries) could still have changed during the study period. An intuitive alternative would be to use contiguous states as control states, but that too has several shortcomings. First, with Oregon's 2015 legalization of recreational marijuana, there was only one possible control state (Idaho) contiguous to Washington. Second, four of Colorado's contiguous states changed from anti-marijuana to medical marijuana states during the study period. Third, although geographically adjacent, contiguous states often have vastly different demographic, roadway, traffic or topographic characteristics. For example, traffic density in Colorado (~250,000 VMT per lane mile of roadway) is more similar to that for distant Vermont (~240,000 VMT/lane mile) than for adjacent Kansas (~110 VMT/lane mile) (Federal Highway Administration, 2007-2017; 2019a); maximum speed limits in Washington (70 mph rural; 60 mph urban) are more similar to those in distant Rhode Island (65 mph rural; 55 mph urban) than in adjacent Idaho (80 mph rural; 80 mph urban) (Governors' Highway Safety Association, 2019b). Finally, there is some evidence that both medical and recreational marijuana laws have cross-border effects in neighboring states, particularly in border counties (Ellison and Spohn, 2017; Hansen et al., 2018a). Although we did not specifically exclude contiguous states from our analysis, having both contiguous and non-contiguous states allowed us to address this by including contiguity as a covariate in our models. Although non-significant, the coefficients for contiguity were consistently negative, suggesting the difference between recreational marijuana states and contiguous states was in fact smaller than the difference between recreational marijuana states and non-contiguous states.

The evidence for increased fatal crashes following recreational marijuana legalization—and particularly after the opening of commercial marijuana dispensaries—stands in contrast to earlier studies finding decreases in traffic fatalities following medical marijuana legalization, at least in some states (Anderson et al., 2013; Santaella-Tenorio et al., 2017). Our analysis incorporated both medical marijuana and anti-marijuana control states. In our difference-in-differences models, the coefficients for medical vs. anti-marijuana control states was consistently positive (although not statistically significant), providing some evidence that the effect of recreational marijuana legalization in Colorado and Washington was greater when compared with medical marijuana states than when compared with anti-marijuana states. This is also apparent when graphing the data for the medical and anti-marijuana states, separately (Fig. 3).

The reasons for this phenomenon are unclear. Perhaps medical marijuana is a substitute for risk-raising prescription and non-prescription substances used for clinical symptoms, while recreational marijuana is not. Perhaps the regulatory environment around medical marijuana legalization conveys protections that do not accompany recreational marijuana legalization. Whatever the reasons, these unexpected findings raise the possibility that legalization of medical and recreational marijuana represent two distinct policy exposures rather than "escalating doses" of the same exposure—and pose very different

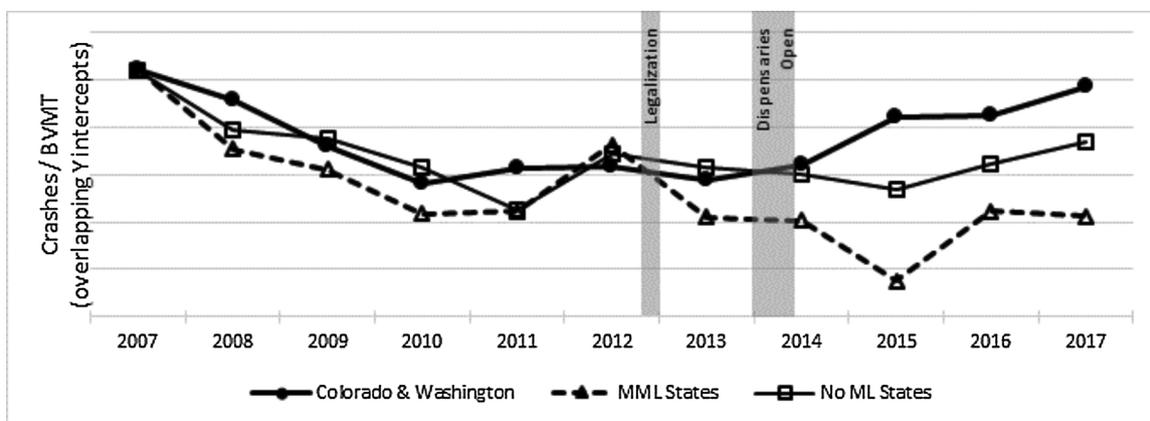


Fig. 3. Longitudinal changes in fatal crash rates for Colorado & Washington compared with medical marijuana and anti-marijuana states, separately (shown with overlapping y intercepts). MML = medical marijuana states; No-ML = anti-marijuana states; BVMT = billion vehicle miles traveled.

risks. This is an area in need of further study.

4.1. Limitations

Limitations of this study include that we did not make any statistical adjustments for multiple analyses, but our use of bootstrap standard errors produces conservative (i.e., wider) bias-corrected confidence intervals (Mooney and Duval, 1993; Haukoos and Lewis, 2005; Anonymous, 2019) and our post-dispensary vs. pre-dispensary results would have remained statistically significant had we used false discovery rate control alpha values (Glickman, Rao & Schultz, 2014). We chose to use a difference-in-differences analysis rather than synthetic control modelling (SCM). SCM techniques are well-suited for analyzing policy case studies (Abadie and Gardeazabal, 2003; Abadie et al., 2010; Krief et al., 2016), but difference-in-differences models are equally appropriate and are more common in the health-related literature. We did not include weather data in our models, but (with the exception of Hawaii) the included states are at similar latitudes. State marijuana laws are dynamic, limiting the number of stable control states available for our analysis. As more states legalize medical and recreational marijuana, it will become increasingly difficult to identify "clean" control states for comparative analyses. Our analysis is limited to fatal crashes; there is no national clearinghouse for data on non-fatal crashes. Finally, it is possible that something else unmeasured coincidentally changed

between 2012 and 2014 in Colorado and Washington but not the control states (or vice-versa) that explains these findings.

5. Conclusion

Fatal crash rates increased in Colorado and Washington after recreational marijuana legalization—and specifically after the opening of commercial recreational marijuana dispensaries—when compared with concurrent changes seen in nine control states that maintained stable medical marijuana or anti-marijuana status. While it is unlikely that these data will lead to the repeal of existing state recreational marijuana laws or slow ongoing legalization efforts in other states, these data can inform policy makers, public health professionals and law enforcement officials of the increased risk of fatal crashes following recreational marijuana legalization so they can begin to craft and implement strategies for mitigating those risks.

Funding

There was no external funding for this work.

Declaration of Competing Interest

None.

Appendix A

Table A1 Detailed population, economic, roadway and traffic characteristics of the included states.

	RML States		No-ML States				MML States				
	CO	WA	ID	KS	NE	SD	HI	MT	NM	RI	VT
BVMT	46.3	55.6	15.4	28.9	19.3	8.4	9.9	11.4	24.3	8.2	7.6
GDP (\$ billion)	246.0	346.0	54.5	122.5	81.9	35.2	65.2	36.1	80.6	47.9	24.7
Per Capita GDP (\$1000)	56.3	59.3	40.3	48.9	51.3	48.9	54.9	41.4	44.8	50.1	43.9
Population (x1 million)	4.8	6.5	1.5	2.8	1.8	0.8	1.3	1.0	2.0	1.1	0.6
Population Density <sup>a</sup>	46.7	97.3	18.1	33.9	23.0	10.5	120.4	6.6	16.4	684.4	64.9
Seatbelt Law	2 <sup>o</sup>	1 <sup>o</sup>	1 <sup>o</sup>	1 <sup>o</sup>	2 <sup>o</sup>	2 <sup>o</sup>	1 <sup>o</sup>	2 <sup>o</sup>	1 <sup>o</sup>	1 <sup>o</sup>	2 <sup>o</sup>
Text/Driving Ban (year)	2009	2008	2012	2010	2010	2014	2013	n/a	2014	2009	2010
Lane Miles (x1000)	88.2	83.4	48.4	140.3	93.4	83.7	4.3	73.2	68.3	6.5	14.4
Traffic Density <sup>b</sup>	525	667	318	206	206	100	2,302	156	356	1,262	528
Hwy. Fund. (\$ billion)	2.9	3.3	0.8	1.5	1.5	0.5	0.3	0.6	0.8	0.5	0.4
Funding/Mile (\$1000)	27.9	39.6	16.5	10.7	16.1	5.4	62.2	8.6	11.0	74.5	27.4
Crashes/BVMT	11.0	9.25	14.2	13.1	11.9	15.6	12.6	22.0	15.2	7.8	8.1

RML = recreational marijuana legalization; No-ML = no marijuana legalization; MML = medical marijuana legalization; BVMT = billion vehicle miles traveled; GDP = gross domestic product; Hwy. Fund. = state revenues used for highways; <sup>a</sup>included only in sensitivity analyses; <sup>a</sup>population per square mile; <sup>b</sup>1,000 vehicle miles traveled per lane mile.

**Table A2**

Detailed regression model for post-legalization vs. pre-legalization periods. Random effects GLS regression. Number of Observations: 1320. Number of Groups: 11. R-Squared: Within = 0.0274. Between = 0.5435. Overall = 0.1802.

	Coef.	Std. Err.	z	P > z	[95% Conf. Interval]	
Post- vs. Pre-Legalization Period	-0.909	0.523	-1.74	0.082	-1.882	-0.346
Exposure vs. Control States	-3.767	8.973	-0.42	0.675	-70.207	0.618
<b>DD</b>	<b>1.176</b>	<b>0.688</b>	<b>1.71</b>	<b>0.087</b>	<b>-0.622</b>	<b>2.122</b>
Medical Marijuana State	1.457	2.284	0.64	0.524	-1.693	5.629
Contiguous State	-2.187	16.527	-0.13	0.895	-33.963	7.964
Population Density	-0.008	0.066	-0.11	0.910	-0.148	0.069
1° (vs. 2°) Seat Belt Law	2.653	16.933	0.16	0.875	-3.953	35.371
Texting Ban	-0.202	0.599	-0.34	0.736	-1.446	1.024
Traffic Density	-0.024	0.059	-0.41	0.682	-0.060	0.082
Per Capita GDP	0.112	0.184	0.61	0.543	-0.174	0.425
Highway Funding per Lane Mile	-0.024	0.026	-0.91	0.360	-0.080	0.021
Constant	7.774	9.100	0.85	0.393	-9.235	22.774
sigma_u	1.599					
sigma_e	3.511					
rho	0.172	(fraction of variance due to u_i)				

DD = interaction term: (post- vs. pre-dispensary period) x (exposure vs. control state), which is synonymous with legalization status in state *s* at time *t*; GDP = gross domestic product.

**Table A3**

Detailed regression model for post-dispensary vs. pre-legalization periods. Random effects GLS regression. Number of Observations: 902. Number of Groups: 11. R-Squared: Within = 0.0264. Between = 0.6257. Overall = 0.1814.

	Coef.	Std. Err.	z	P > z	[95% Conf. Interval]	
Post-Dispensary vs. Pre-Legalization Period	-0.636	0.563	-1.13	0.259	-1.986	0.393
Exposure vs. Control States	-3.072	5.203	-0.59	0.555	-26.289	1.217
<b>DD</b>	<b>1.832</b>	<b>0.789</b>	<b>2.32</b>	<b>0.020</b>	<b>0.353</b>	<b>3.710</b>
Medical Marijuana State	0.940	3.103	0.30	0.762	-2.009	13.060
Contiguous State	-1.828	30.308	-0.06	0.952	-43.768	13.209
Population Density	-0.006	0.089	-0.06	0.950	-0.195	0.255
1° (vs. 2°) Seat Belt Law	2.147	31.034	0.07	0.945	-219.467	20.386
Texting Ban	-0.224	0.758	-0.29	0.768	-1.421	1.100
Traffic Density	-0.017	0.040	-0.43	0.666	-0.047	0.131
Per Capita GDP	0.015	0.189	0.08	0.936	-0.407	0.393
Highway Funding per Lane Mile	-0.025	0.024	-1.04	0.298	-0.093	0.005
Constant	12.049	8.615	1.40	0.162	-0.505	33.567
sigma_u	1.008					
sigma_e	3.547					
rho	0.075	(fraction of variance due to u_i)				

DD = interaction term: (post- vs. pre-dispensary period) x (exposure vs. control state), which is synonymous with legalization status in state *s* at time *t*; GDP = gross domestic product.

**Table A4**

Detailed regression model for post-dispensary vs. pre-dispensary periods. Random effects GLS regression. Number of Observations: 902. Number of Groups: 11. R-Squared: Within = 0.0194. Between = 0.6003. Overall = 0.1825.

	Coef.	Std. Err.	z	P > z	[95% Conf. Interval]	
Post- vs. Pre-Dispensary Period	-0.554	0.738	-0.75	0.453	-2.487	0.365
Exposure vs. Control States	-3.201	4.903	-0.65	0.514	-25.346	1.272
<b>DD</b>	<b>1.568</b>	<b>0.703</b>	<b>2.23</b>	<b>0.026</b>	<b>0.665</b>	<b>3.48</b>
Medical Marijuana State	1.127	5.287	0.21	0.831	-1.111	9.188
Contiguous State	-1.601	13.732	-0.12	0.907	-11.777	100.529
Population Density	-0.007	0.098	-0.07	0.946	-0.195	0.281
1° (vs. 2°) Seat Belt Law	1.923	14.392	0.13	0.894	-17.255	12.450
Texting Ban	-0.157	1.138	-0.14	0.891	-2.359	1.953
Traffic Density	-0.022	0.045	-0.48	0.629	-0.038	0.130
Per Capita GDP	0.060	0.232	0.26	0.797	-0.166	0.726
Highway Funding per Lane Mile	-0.015	0.026	-0.60	0.551	-0.078	0.180
Constant	-9.646	11.381	0.85	0.397	-22.900	21.545
sigma_u	1.316					
sigma_e	3.502					
rho	0.124	(fraction of variance due to u_i)				

DD = interaction term: (post- vs. pre-dispensary period) x (exposure vs. control state), which is synonymous with legalization status in state *s* at time *t*; GDP = gross domestic product.

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