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A longitudinal analysis of the effectiveness of California's ban on cellphone use while driving

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ABSTRACT

Cellphone use while driving is an increasingly serious threat for traffic safety and is prohibited in many jurisdictions. In California, the use of handheld cellphones while driving has been prohibited since July 1, 2008. Using interrupted time series analysis, this study explores the effectiveness of the ban by specifically analyzing the crashes caused by cellphone usage in California from 2002 to 2014. These crashes were thought to be able to reflect the role of the ban more accurately than total crashes. The ban was found effective in reducing the cellphone usage-caused crashes in terms of both crash frequency and crash proportion. The study also confirms that crashes caused by cellphone use produce more severe outcomes than other crashes. These findings show that the ban on handheld cellphone use while driving plays an important role for improving traffic safety in California. In addition, it is found that the ban motivates drivers to switch from handheld cellphones to hands-free cellphones, but in terms of crash severity, hands-free cellphone usage and handheld cellphone usage do not show significant differences. These findings support a complete ban on cellphone use while driving–not just a prohibition of handheld cellphone use. The study results are expected to provide new insights for future policy-making related to cellphone use while driving.

1. Introduction

The advent of cellphones greatly improves quality of life, but at the same time, cellphone- distracted driving has increasingly become a great threat to traffic safety. In 2011, 385 fatal and 21,000 injury crashes in the United States (U.S.) involved at least one driver using a cellphone (National Highway Traffic Safety Administration, 2013). As early as in 1997, the use of a cellphone while driving was reported to quadruple the risk of a collision (Redelmeier and Tibshirani, 1997). Since then, many studies have assessed the influence of cellphone distraction on driving. These include on-road field studies (Klauer et al., 2014; Young et al., 2013; Ferlazzo et al., 2008), controlled test-track studies (Owens et al., 2011; Hancock et al., 2003), and driving simulator studies (Beede and Kass, 2006; Charlton, 2009; Crisler et al., 2008; Kass et al., 2007; Strayer et al., 2006, 2003; Strayer and Drews, 2004; Schlehofer et al., 2010; Strayer and Drews, 2007). These analyses affirmed that cellphone usage can distract drivers, with effects on reaction time, visual search, lane keeping, speed control, and other driving tasks. For example, at signalized intersections, cellphone-distracted drivers were found to need more reaction time and have more traffic violations, such as red light running or stopping at green lights (Hancock et al., 2003; Patten et al., 2004; Strayer and Drews, 2004; Beede and Kass, 2006; Strayer et al., 2006; Cooper and Strayer,

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2008; Horrey et al., 2008; Young et al., 2013). Another study observed that drivers talking on the phone tended to stop conservatively when approaching signalized intersections in the yellow phase (Liu et al., 2012).

In response to concerns about cellphone distraction, many states have passed laws to regulate cellphone use while driving in U.S. As of April 2018, 16 states, the District of Columbia, Puerto Rico, Guam and the U.S. Virgin Islands prohibited all drivers from using handheld cellphones, but no state banned hands-free cellphone use (Governors Highway Safety Association, 2018). Accompanying these bans, there has been a controversy about their effectiveness in practice. Some studies find the bans effective:

- Nikolaev et al. (2010) analyzed the yearly county-level fatal accident rate and person injury accident rate in New York State from 1997 to 2007, where handheld cellphone usage was prohibited after December 1, 2001. They found the law was effective in reducing traffic crashes for most counties.
- Sampaio (2014) analyzed the fatality rate data from the Fatality Analysis Reporting System (FARS) in New York State from 1996 to 2005 with the Synthetic Control Methods (SCM), and found that the ban led to a 9% decrease in fatality rates.
- Lim and Chi (2013a) analyzed the non-alcohol related fatal crashes involving drivers under the age of 21 with the FARS data of 48 states from 1996 to 2010, and found that handheld cellphone bans reduced fatal crashes.

Other studies find the bans ineffective:

- Trempel et al. (2011) analyzed the monthly collision claim frequency data from the Highway Loss Data Institute before and after the enactment of handheld phone bans in California, Connecticut, New York, and the District of Columbia, but found no evidence of a decrease in crash risk.
- Williams-Bergen et al. (2011) reviewed the distracted driving research as of January 2011 and concluded that "there is no evidence that cell phone or texting bans have reduced crashes".

A third group of studies finds mixed results:

- Jacobson et al. (2012) analyzed the county-level accident rates for Pennsylvania and New York from 1997 to 2008, and found that bans on handheld device use while driving reduced personal injury accident rates in counties with high levels of driver density, but also increased accident rates in counties with low driver density levels.
- Lim and Chi (2013b) analyzed the state-level panel fatal crash rates from 2000 to 2010 in U.S., and found that cellphone bans significantly reduced fatal crashes rates for drivers between 18 and 34 years of age, but not drivers older than 55.

Thus, it is still unclear whether these laws had the desired effects in improving traffic safety (McCartt et al., 2014). Studies focusing on the state of California (the research target of this paper) have also produced inconsistent conclusions. In California, since July 1, 2008 drivers under 18 years of age have been prohibited from using any form of wireless telephone while driving (California State Legislature, 2008a), while drivers 18 years of age and older may operate hands-free cellphones (e.g. earpiece or speakerphone) (California State Legislature, 2008b). Kwon et al. (2014) analyzed the monthly handheld, hands-free, handheld & hands-free, and all-cellphone usage crash data from 2006 to 2010 from the California Statewide Integrated Traffic Records System (SWITRS), and thought the law was one of the primary factors in reducing cellphone-related collisions. Nevertheless, Burger et al. (2014) analyzed daily traffic accident data for California from January 1, 2008 to December 31, 2008, and found no evidence that the ban on handheld cellphone use led to a reduction in traffic accidents in its first six months. However, only 1 year of data might not be long enough to identify the effects of the ban.

Analysis of cellphone-related crashes is meaningful in exploring the ban effects. However, rather than focusing solely on crashes caused by cellphone usage, most existing studies analyzed all crash data before and after the bans (Nikolaev et al., 2010; Trempel et al., 2011; Jacobson et al., 2012; Lim and Chi, 2013a, 2013b; Burger et al., 2014), probably because many states do not collect cellphone usage information in their crash reports. When using all the crash data, even with careful case-control, it might be still difficult to identify the roles of the bans. This is due to the fact that cellphone usage-caused crashes represent only a small proportion of total crashes as shown later in this study, and many factors can contribute to changes in crash frequency. Inaccurate crash data could potentially affect the credibility of these studies.

Most of the previous studies analyzed crash frequency or crash rate data, which are meaningful but might not give a full picture due to changes in overall crash trends. For example, if cellphone usage-caused crashes decreased after the enactment of a ban but other crashes decreased more, it would be difficult to conclude that the ban was effective. Thus, a better measure is the proportion of cellphone usage-caused crashes out of total crashes, which can take general trends into account. In addition, from a policy perspective, it is also important to understand whether drivers would switch from handheld phones to hand-free phones under the ban (McCartt et al., 2010, 2014; Trempel et al., 2011; Carpenter and Nguyen, 2015).

In terms of crash outcomes, although cellphone usage while driving has been shown to be risky, few studies have analyzed whether cellphone usage-caused crashes result in more severe injuries than other crashes. Moreover, although handheld and hands-free cellphones currently have different legal statuses, there is a lack of research exploring whether they produce different safety outcomes. Identifying these differences is crucially important for policy decisions related to the use of cellphones while driving.

Using 2002–2014 California crash data from the Highway Safety Information System (HSIS), this study is designed to assess the long-term trends for cellphone usage-caused crashes in California, the effectiveness of the ban, and the severity of cellphone usage-caused crashes. The remainder of this paper is organized as follows: Section 2 explains the data collection and gives a preliminary

Table 1
Yearly cellphone usage-caused crashes and total crashes in California (2002–2014).

Year	Cellphone usage-caused crashes by cellphone type			Total Crashes	Proportion of cellphone usage-caused crashes in total crashes
	Handheld	Hands-free	Unknown		
2002	0	0	526	164,794	0.32%
2003	40	2	511	176,394	0.31%
2004	407	17	86	180,411	0.28%
2005	569	53	32	179,759	0.36%
2006	568	30	15	175,601	0.35%
2007	585	34	17	166,828	0.38%
2008	378	50	5	146,222	0.30%
2009	282	52	1	139,950	0.24%
2010	266	53	1	143,983	0.22%
2011	274	58	2	140,390	0.24%
2012	298	55	0	135,907	0.26%
2013	375	74	1	137,202	0.33%
2014	419	56	1	141,118	0.34%

analysis of crash data; Section 3 discusses the effectiveness of the cellphone usage ban; Section 4 discusses the severity of cellphone usage caused-crashes. Finally, conclusions and future research needs are discussed in Section 5.

2. Data collection and preview

The crash data collected by the California Highway Patrol (CHP) from 2002 to 2014 were obtained from HSIS. CHP is responsible for investigating crashes on all freeways, other State routes and county roads outside municipal areas in California (Nujjetty et al., 2014). Among more than 400,000 accidents occurring in California each year, 150,000 of them are investigated by CHP. Causes of accidents are recorded in the raw data, where 'handheld cellphone', 'hands-free cellphone', and 'cellphone' are taken as three separate causes. Although the California handheld cellphone ban was not implemented until July 1, 2008, 'cellphone' has been recorded as a cause for crashes since January 1, 2001. In crash records after July 1, 2003, 'cellphone' was further divided into 'handheld cellphone' and 'hands-free cellphone' categories. Thus, in this study, the cellphone-usage caused crashes include all the crashes where handheld cellphone, hands-free cellphone, or cellphone is recorded as the cause. Since the following analysis involves in driver information, this study only focuses on analyzing the crashes where information of vehicles at fault are available. A summary of yearly crash frequencies by cause is presented in Table 1. Figs. 1 and 2 show the monthly cellphone-usage caused crash frequencies and their proportions out of total crash frequencies, respectively.

It can be found that:

(1) Cellphone usage-caused crashes represented only a very small proportion of total crashes, which means that it might be difficult to exclude the effects of confounding factors when exploring the effectiveness of bans by analyzing all the crash data.
(2) Both cellphone usage caused-crashes and total crashes had obvious declines in 2008. Total crashes continuously decreased from 2002 to 2008, and then kept consistent. Cellphone usage-caused crashes continuously decreased from 2005 to 2009, but then increased from 2010 to 2014.
(3) Handheld cellphones caused many more crashes than hands-free cellphones, which hints that handheld cellphone usage might be more dangerous than hands-free cellphone usage.

Table 2 gives the composition of crashes by at-fault driver age, for drivers between the ages of 14 and 105. The drivers of cellphone usage-caused crashes were 5.81 years younger than those of other crashes on average. That is, young drivers are more likely to have cellphone usage-caused crashes than other crashes, which is probably because young people use cellphones more often than old people (Pöysti et al., 2005).

Table 3 shows the composition of crashes by driver gender, where crashes without driver gender information were excluded. Male drivers had many more cellphone usage-caused crashes than females, which is also consistent with previous findings (Pöysti et al., 2005). Notably, males were involved in 92.3% more other crashes than females, but only 46.1% more cellphone usage-caused crashes than females. While this implies that females might be more likely to have a crash when using cellphones while driving than males, the reasons are unclear.

3. Effectiveness of handheld device ban in California

Monthly crash data are typical time series data, and the implementation of the handheld device ban can be thought as an intervention. Thus, they are typical Interrupted Time Series (ITS) data suitable for analysis using the quasi-experimental interrupted time series design, which has been proven effective in many studies (Fuller et al., 2012; Bonander et al., 2014, 2015; Huitema et al., 2014; Morrison et al., 2017). The quasi-experimental interrupted time series design is especially useful when the numbers of data

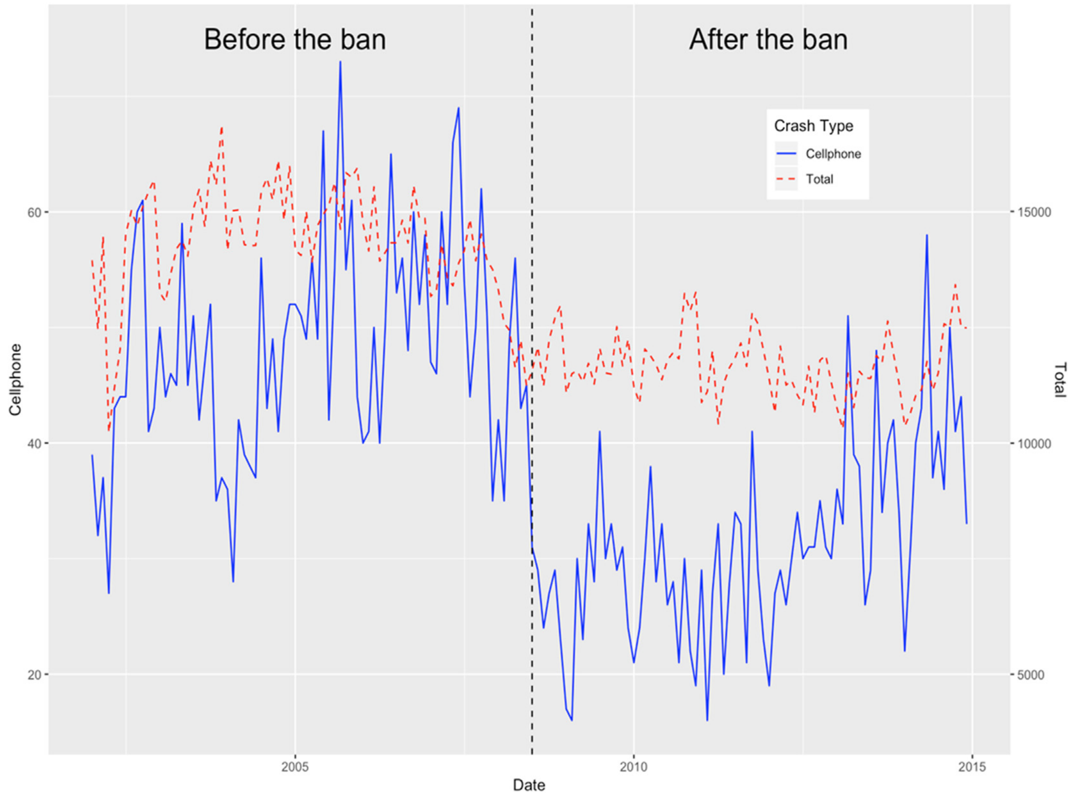

Fig. 1. Frequencies of monthly cellphone usage-caused crashes and total crashes in California (2002–2014).

points are equal before and after the intervention (Zhang et al., 2011), which is the case in this data set. To control for changes in traffic volume, the crash data set has been augmented with monthly vehicle miles travelled (VMT) data for California state highways (Caltrans, 2018). A standard ITS regression model can be built as follows (Bernal et al., 2017):

$$Y_t = \beta_0 + \beta_1 Intervention_t + \beta_2 t + \beta_3 t(Intervention_t) + \beta_4 X_t \tag{1}$$

where Y_t is the value of the dependent variable at time point t; β_0 is the baseline level at $t = 0$; β_1 is the level change due to the intervention; β_2 represents the pre-intervention trend; β_3 is the slope change due to the intervention; $Intervention_t$ is a dummy variable indicating the pre-intervention (0), or post-intervention (1); $t\,(=1, \cdots, T)$ is the time point since the start of the study; X_t is the value of covariate X at time point t; and T is the number of time points.

As to this study, the intervention, i.e. the ban, is expected to immediately show some constant effects (β_1) in preventing cellphone usage-caused crashes after it is implemented, i.e. the so-called level change. However, with the possible decrease of enforcement campaigns and public attention over time (McCartt and Geary, 2004), some rebound effects (β_3) are expected to appear over time, i.e. the so-called direction change.

All the models in this study were built in R, an open-source statistical analysis software (R Core Team, 2016). The crash frequency model was estimated with the “MASS” package (Venables and Ripley, 2003), and the crash proportion models were estimated with the “betareg” package (Cribari-Neto and Zeileis, 2010).

3.1. Monthly cellphone usage-caused crash frequency analysis

The monthly cellphone usage-caused crash frequency is analyzed to determine whether it was influenced by the handheld device ban. Since crash frequency data are count data and over-dispersed in this study, a Negative Binomial (NB) regression model was built as shown in Eqs. (2) and (3). The estimated results are shown in Table 4.

$$Y_t \sim NB(\mu_t, \theta) \tag{2}$$

$$\log(\mu_t) = \beta_0 + \beta_1 Intervention_t + \beta_2 t + \beta_3 t(Intervention_t) + \beta_4 VMT_t \tag{3}$$

where Y_t is the cellphone usage-caused crash frequency at time point $t\,(=1, \cdots, 156)$; μ_t is the mean of Y_t; θ is the dispersion parameter; VMT_t is the VMT at time point t; and β_4 is the regression coefficient for VMT.

Since the coefficient for Intervention is significantly negative, it means that the cellphone usage-caused crashes immediately decreased after the implementation of the ban in California. The statistical model suggests that on average, these crashes decreased

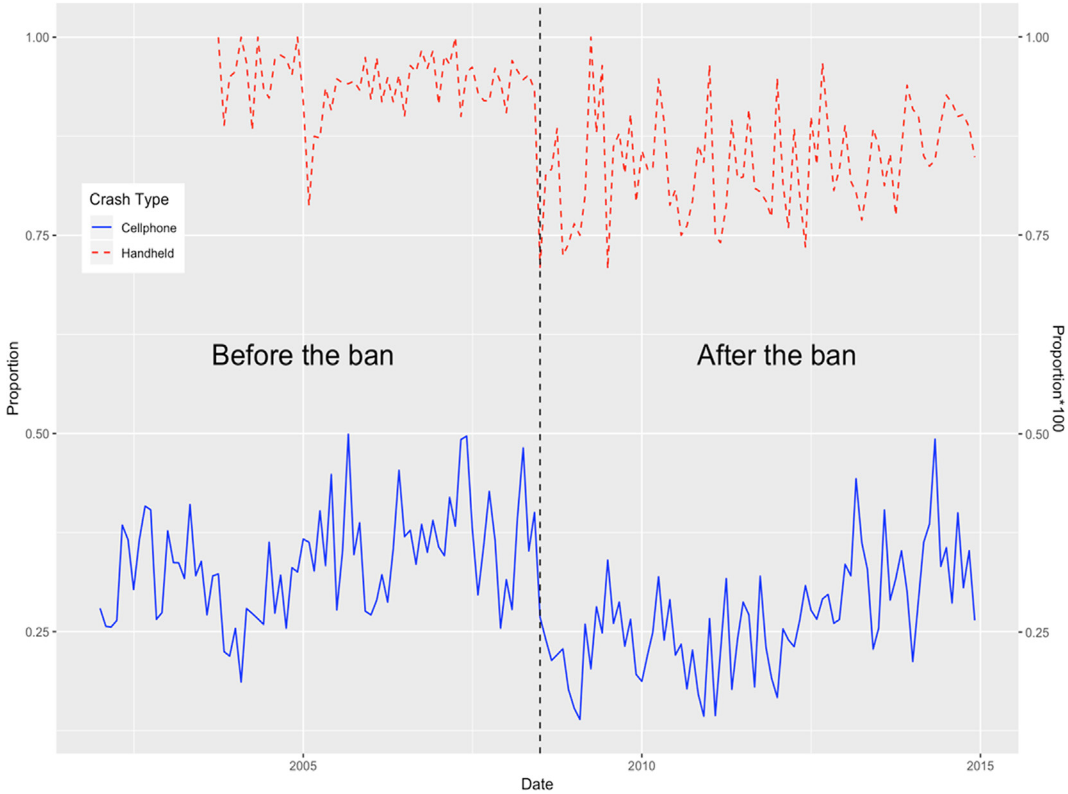

Fig. 2. Proportions of monthly cellphone usage-caused crashes in total crashes and handheld cellphone usage-caused crashes in handheld and hands-free cellphone usage-caused crashes in California (2002–2014).

Table 2
The composition of crashes by driver age.

Driver age (Year)	Cellphone usage-caused crashes	Other crashes
Mean	32.11	36.15
Median	29	32
Quantile (5%, 95%)	(17,61)	(17,74)

Table 3
The composition of crashes by driver gender.

Driver gender	Cellphone usage-caused crashes	Other crashes
Male	3660	1,233,975
Female	2505	641,896
Male/Female	1.461	1.923

Table 4
Estimated results of the NB regression model for the monthly cellphone usage-caused crash frequencies.

Variable	Estimate	Standard Error	95% Confidence Interval
Intercept	2.030	0.343	(1.353, 2.707)*
Intervention	−1.090	0.130	(−1.345, −0.836)*
Time point	0.002	0.001	(0.000, 0.003)
Time point * Intervention	0.005	0.001	(0.002, 0.007)*
VMT	0.119	0.023	(0.073, 0.166)*

* Significant at 0.05.

Table 5
Estimated results of the Beta regression model for the proportion of cellphone usage-caused crashes out of total crashes.

Variable	Estimate	Standard Error	95% Confidence Interval
Intercept	−7.121	0.346	(−7.799, −6.443)*
Intervention	−0.873	0.129	(−1.126, −0.620)*
Time point	0.003	0.001	(0.001, 0.004)*
Time point * Intervention	0.004	0.001	(0.001, 0.006)*
VMT	0.089	0.024	(0.043, 0.135)*

* Significant at 0.05.

by 66.4%. Meanwhile, the Time point shows insignificant effects, which means that if the ban had not been implemented, the cellphone usage-caused crash frequencies would have been expected to remain consistent over time. However, the interaction of Time point and Intervention is significantly positive, which means after implementing the law, the cellphone usage-caused crashes also gradually rebounded. On average, they increased 0.47% per month. Thus, it is possible to conclude that the ban was effective in reducing cellphone usage-caused crashes, but this effect has gradually weakened over time. This finding is generally consistent with the trend in Fig. 1, and also in accordance with the observations of McCartt and Geary (2004), where the overall handheld cellphone use rate in New York declined shortly after passing the law, but rebounded one year later. A possible explanation is that publicity and law enforcement of the ban might decline over time (McCartt and Geary, 2004), and thus drivers did not follow the law as strictly as they did in the beginning.

3.2. Monthly cellphone usage-caused crash proportion analysis

In many situations it is preferable to analyze proportion data instead of the total number of cases, since it is less vulnerable to exogenous effects (Bonander et al., 2014). For example, motor vehicle crash trends can be influenced by weather, road construction, vehicle technologies, and other factors that are beyond the scope of this study. To minimize the effects of these factors, the proportion of cellphone usage-caused crashes out of total crashes was analyzed to explore the effects of the ban from a different perspective. A Beta regression model was built for the proportion data analysis as shown in Eqs. (4) and (5). The estimation results are shown in Table 5.

$$Y_t \sim Beta(\mu_t, \phi) \tag{4}$$

$$\text{logit}(\mu_t) = \beta_0 + \beta_1 Intervention_t + \beta_2 t + \beta_3 t(Intervention_t) + \beta_4 VMT_t \tag{5}$$

where Y_t is the proportion of cellphone usage-caused crashes out of total crashes at time point $t\,(=1, \cdots, 156)$; $0 < \mu_t < 1$, is the mean of Y_t; $\phi > 0$, is the precision parameter.

The coefficient for Intervention is significantly negative, which means the ban was effective in reducing the proportion of crashes caused by cellphone usage. On average, the odds ratio decreased by 58.2% for the proportion of total crashes caused by cellphone usage. Meanwhile, coefficients of both Time point and the interaction of Time point and Intervention are significantly positive, which means the proportion of cellphone usage-caused crashes in total crashes had been gradually increasing over time, confirming that the cellphone usage is an increasingly serious issue for traffic safety. Another interesting finding is that VMT showed significantly positive effects, which means the proportion of cellphone usage-caused crashes in total crashes increased when VMT increased. A possible explanation is that people who drive a lot use cellphones more often than those who only drive a little (Pöysti et al., 2005). However, further investigation is needed to figure out whether this is true in California.

In addition, based on the estimation results of the NB regression model for the crash frequency and the Beta regression model for the crash proportion, the effects of the ban are calculated in terms of the yearly reduced cellphone usage-caused crash counts after its implementation. The results are shown in Table 6. It can be found that although the estimated values of the two approaches are not exactly the same, both of them indicate that the cellphone usage caused-crashes were greatly reduced. On average, there were about 220 cellphone usage caused-crashes reduced per year after the ban implementation.

Table 6
The yearly reduced cellphone usage-caused crash counts after the ban implementation by the NB regression model and the Beta regression model.

Year	NB Regression	Beta Regression	Average	Actually Occurred
2008 (July to December)	155	116	136	163
2009	295	214	255	335
2010	281	211	246	320
2011	266	195	230	334
2012	248	177	212	353
2013	232	167	199	450
2014	216	159	187	476

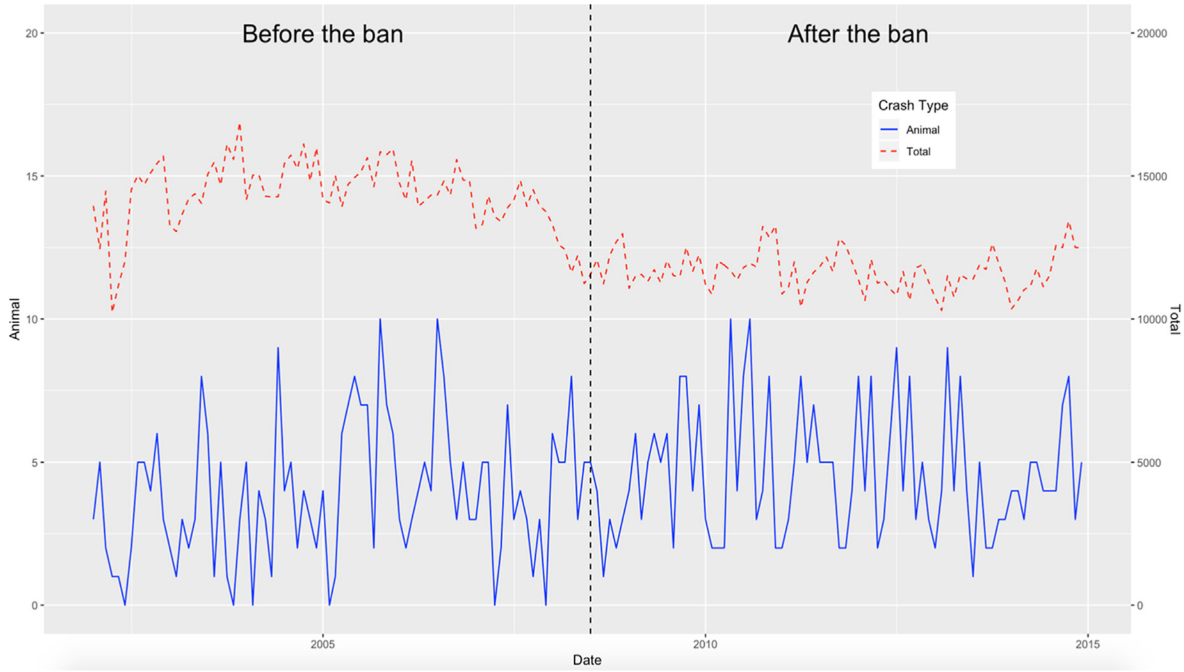

Fig. 3. Frequencies of monthly animal-caused crashes and total crashes in California (2002–2014).

3.3. Sensitivity analysis

To further check the credibility of above analysis, a sensitivity analysis is made with the animal caused-crashes. It is reasonable to assume that the cellphone usage ban would not directly influence the animal-caused crashes. Thus, the intervention is expected to show insignificant effects in the estimation results of regression analysis to animal-caused crashes. Fig. 3 shows the frequencies of monthly animal-caused crashes and total crashes in California. Table 7 shows the estimated results of the NB regression model for the animal-caused crash frequencies, and Table 8 shows the estimated results of the Beta regression model for the proportion of animal-caused crashes out of total crashes. It can be found that the coefficients of Intervention are insignificant in both models. Therefore, it means the ban did not show significant effects on the animal-caused crashes, which demonstrates the reliability of above analysis in another view.

3.4. Monthly handheld cellphone usage-caused crash proportion analysis

The California legislation prohibited only handheld device usage while driving. Since hands-free device usage was not restricted, this poses a question: did the ban reduce the overall use of cellphones while driving, or simply provoke a switch to hands-free devices? Aiming at this question, another Beta regression model was built to analyze the proportion of hands-free cellphone usage-caused crashes among total cellphone usage-caused crashes as shown in Eqs. (6) and (7). The estimation results are shown in Table 9. Since the cellphone type information was not available until 2004 as shown in Table 1, only post-2003 crash data was used for this analysis.

$$Y_t \sim Beta(\mu_t, \phi) \tag{6}$$

$$\mathrm{logit}(\mu_t) = \beta_0 + \beta_1 Intervention_t + \beta_2 t + \beta_3 t(Intervention_t) + \beta_4 VMT_t \tag{7}$$

Table 7
Estimated results of the NB regression model for the monthly animal-caused crash frequencies.

Variable	Estimate	Standard Error	95% Confidence Interval
Intercept	−1.922	1.004	(−3.894, 0.037)
Intervention	0.416	0.336	(−0.249, 1.075)
Time point	0.004	0.003	(−0.002, 0.010)
Time point * Intervention	−0.004	0.004	(−0.012, 0.003)
VMT	0.208	0.068	(0.075, 0.341)*

* Significant at 0.05.

Table 8
Estimated results of the Beta regression model for the proportion of animal-caused crashes out of total crashes.

Variable	Estimate	Standard Error	95% Confidence Interval
Intercept	−10.985	1.027	(−12.999, −8.972)*
Intervention	0.627	0.333	(−2.620, 1.279)
Time point	0.004	0.003	(−1.727, 0.011)
Time point * Intervention	−0.004	0.004	(−0.012, 0.004)
VMT	0.172	0.070	(0.036, 0.308)*

* Significant at 0.05.

Table 9
Estimated results of the Beta regression model for the proportion of handheld cellphone usage-caused crashes out of handheld and hands-free cellphone usage-caused crashes.

Variable	Estimate	Standard Error	95% Confidence Interval
Intercept	3.496	1.411	(0.730, 6.263)*
Intervention	−1.489	0.374	(−2.221, −0.756)*
Time point	−0.012	0.007	(−0.025, 0.002)
Time point * Intervention	0.012	0.008	(−0.003, 0.027)
VMT	−0.025	0.092	(−0.206, 0.155)

* Significant at 0.05.

where Y_t is the proportion of handheld cellphone usage-caused crashes out of handheld and hands-free cellphone usage-caused crashes at time point $t\,(=1,\cdots,132)$.

As is shown in Table 9, the coefficient for Intervention is significantly negative, which means that after implementing the ban, the proportion of handheld cellphone usage-caused crashes out of handheld and hands-free cellphone usage-caused crashes significantly decreased. On average, its odds ratio decreased by 77.4%. This implies that the ban might greatly provoke drivers to switch from handheld cellphones to hands-free cellphones, a phenomenon which has been reported in many studies (Trempel et al., 2011; McCartt et al., 2014; Carpenter and Nguyen, 2015). Meanwhile, both Time point and the interaction of Time point and Intervention show insignificant effects. That is, the proportion of handheld cellphone usage-caused crashes out of handheld and hands-free cellphone usage-caused crashes keeps consistent over time without the ban. Although hands-free devices, such as Bluetooth earphones, are increasingly popular, it seems drivers still tend to hold phones to make calls. In addition, VMT is also insignificant.

4. Severity analysis for cellphone usage-caused crashes

In California, crashes are divided into five categories by severity: fatal, severe injury, other visible injury, complaint of pain, and property damage only (PDO). The proportion of crashes by severity is shown in Table 10. Notably, the cellphone usage-caused crashes have lower proportions of PDO crashes than other crashes. In addition, the handheld cellphone usage-caused crashes have higher proportions of fatal and severe injury crashes than hands-free cellphone usage-caused crashes. Due to the small number of fatal and severe injury crashes, for analytical purposes they were merged with other visible injury crashes and labeled as “injury crashes”. Similarly, the complaint of pain crashes were merged with PDO crashes and labeled as “non-injury crashes”. Thus, crashes were reclassified into two categories in the following analysis: injury crashes and non-injury crashes. Table 11 shows the composition of the final used data in this section by cause and injury.

4.1. Severity analysis of cellphone usage-caused crashes versus other crashes

Although cellphone usage while driving has been shown to be able to increase crash risk, to the best knowledge of the authors, no

Table 10
The proportions of crashes by severity.

Severity	Cellphone usage-caused crashes			Other crashes
	Handheld	Hands-free	Unknown	
Fatal	1.0%	0.9%	1.0%	0.9%
Severe injury	2.4%	1.3%	1.5%	2.2%
Other visible injury	12.3%	11.3%	13.2%	11.0%
Complaint of pain	24.5%	29.4%	25.6%	22.3%
PDO	59.8%	57.1%	58.6%	63.7%
# of crashes	4441	531	1193	1,875,871

Notes: the data set includes only crashes involving drivers aged between 14 and 105 with known gender (female or male).

Table 11
The composition of final used crashes by cause and injury.

Severity	Cellphone usage-caused crashes				Other crashes
	Handheld	Hands-free	Unknown	Total	
Injury	697	72	188	957	264,019
Non-injury	3,744	459	1,005	5,208	1,611,852
Total	4,441	531	1,193	6,165	1,875,871

studies have explored whether cellphone usage-caused crashes produce more severe outcomes than other crashes, which is critical information for cellphone regulation and policymaking. To address this knowledge gap, a logistic regression model was built using the previously-described crash data as specified in Eqs. (8) and (9), with driver gender and driver age as covariates. Drivers were divided into three age categories: young (≤25), middle (25–65), and old (≥65). The results of the model estimation are shown in Table 12.

$$Z_i \sim Bernoulli(p_i) \tag{8}$$

$$\log\left(\frac{p_i}{1-p_i}\right) = r_0 + r_1 * Cellphone_i + r_2 * Young_i + r_3 * Old_i + r_4 * Male_i + r_5 * Young_i * Male_i + r_6 * Old_i * Male_i \tag{9}$$

where Z_i is the severity level of the *ith* crash, $Z_i = 1$ if it is an injury crash, and $Z_i = 0$ if it is a non-injury crash; p_i is the probability of the *ith* crash being an injury crash; r_0 is the intercept; $r_1, \ldots, r_6$ are regression coefficients; $Cellphone_i = 1$ if the *ith* crash was caused by cellphone usage, otherwise $Cellphone_i = 0$; $Young_i = 1$ if the driver of the *ith* crash is young, otherwise $Young_i = 0$; $Old_i = 1$ if the driver of the *ith* crash is old, otherwise $Old_i = 0$; $Male_i = 1$ if the driver of the *ith* crash is male, otherwise $Male_i = 0$; $Young_i * Male_i$ and $Old_i * Male_i$ are interaction terms of age and gender.

The "Cellphone" variable shows significantly positive effects, which means cellphone usage-caused crashes are more likely to cause injuries than other crashes. On average, the odds ratio of a cellphone usage-caused crash leading to injuries is 1.115 times of other crashes. This finding further demonstrates the risk of cellphone usage while driving. Old drivers do not show significant differences from middle-aged drivers, whereas young drivers, male drivers, and young male drivers are more likely to be injured in crashes, which is understandable, since these groups have often been found to take more driving risks than their female and middle-aged counterparts. Meanwhile, old male drivers are found to be less likely to be injured in crashes.

4.2. Severity analysis of hands-free cellphone usage-caused crashes versus handheld cellphone usage-caused crashes

This part of the analysis focused on exploring whether handheld cellphone usage-caused crashes have more severe outcomes than those caused by hands-free cellphone usage. This is very important from a policy perspective, considering that there are very few restrictions on hands-free cellphone use in U.S., but to the best knowledge of the authors, no previous studies of this issue were found. Only the hands-free and handheld cellphone usage-caused crash data was used in analysis. A logistic regression model was built in the form shown in Eqs. (10) and (11). The estimated results are shown in Table 13.

$$Z_i \sim Bernoulli(p_i) \tag{10}$$

$$\log\left(\frac{p_i}{1-p_i}\right) = r_0 + r_1 * Handsfree_i + r_2 * Young_i + r_3 * Old_i + r_4 * Male_i + r_5 * Young_i * Male_i + r_6 * Old_i * Male_i \tag{11}$$

where Z_i is the severity level of the *ith* cellphone usage-caused crash, $Z_i = 1$ if it is an injury crash, and $Z_i = 0$ if it is a non-injury crash; p_i is the probability of the *ith* cellphone usage-caused crash being an injury crash; $Hands-free_i = 1$ if the *ith* crash was caused by hands-free cellphone usage, and $Hands-free_i = 0$ if the *ith* crash was caused by handheld cellphone usage.

The "Hands-free" variable is insignificant. Thus, the handheld and hands-free crashes did not show significant differences in terms

Table 12
Estimated results of the logistic regression to the severity of all the crashes.

Variable	Estimate	Standard Error	95% Confidence Interval
Intercept	−1.929	0.005	(−1.939, −1.919)*
Cellphone	0.109	0.035	(0.040, 0.178)*
Age – Young (≤25)	0.073	0.008	(0.057, 0.088)*
Age – Old (≥65)	0.024	0.015	(−0.004, 0.053)
Male	0.145	0.006	(0.133, 0.156)*
Age – Young (≤25): Male	0.045	0.010	(0.026, 0.064)*
Age – Old (≥65): Male	−0.216	0.017	(−0.250, −0.182)*

* Significant at 0.05.

Table 13
Estimated results of the logistic regression to the severity of cellphone usage-caused crashes.

Variable	Estimate	Standard Error	95% Confidence Interval
Intercept	−1.630	0.086	(−1.802, −1.464)*
Hands-free	−0.163	0.134	(−0.433, 0.093)
Age – Young (≤25)	0.076	0.121	(−0.160, 0.313)
Age – Old (≥65)	−0.206	0.544	(−1.436, 0.753)
Male	−0.087	0.108	(−0.297, 0.125)
Age – Young (≤25): Male	−0.098	0.162	(−0.416, 0.220)
Age – Old (≥65): Male	−0.128	0.726	(−1.561, 1.361)

* Significant at 0.05.

of the crash severity, which kind of supports a complete prohibition of cellphone use while driving from another view (Huang et al., 2010; Harding, 2013). It should be noted that this study does not explore whether drivers are more likely to have crashes when they use handheld cellphones than hands-free cellphones, which needs further investigation.

5. Conclusions and discussions

In response to traffic crashes related to cellphone use while driving, about 20 states and territories prohibit the use of handheld cellphones in U.S. However, there is longstanding controversy on the effectiveness of these bans. This study explored this issue using 2002–2014 crash data from California, where drivers aged 18 and older were prohibited from using handheld cellphones after July 1, 2008. In contrast to previous studies which usually analyzed crashes of all causalities, this study specifically analyzed the cellphone usage-caused crashes, which were more appropriate for the research objective but rarely used before. In addition to crash frequency, this study also analyzed changes in the proportion of cellphone usage-caused crashes out of total crashes. The use of this proportion information helps reduce the effects of exogenous factors, and the results are believed to be able to reflect the effects of the ban more accurately than only analyzing crash frequency.

The handheld cellphone ban in California was found to be very effective in reducing cellphone usage-caused crashes, especially handheld cellphone usage-caused crashes. Statistical modeling indicates that on average, the ban reduced 66.4% of cellphone usage-caused crashes, and the odds ratio of the proportion of cellphone usage-caused crashes out of total crashes decreased by 58.2%. Compared to California crashes in general, the study confirmed that the cellphone usage-caused crashes produced more severe outcomes in terms of injury severity. Meanwhile, the ban was found to motivate many drivers to switch from handheld cellphones to hands-free cellphones, but in terms of crash severity the hands-free cellphone usage-caused crashes and the handheld cellphone usage-caused crashes did not show significant differences. This finding supports the notion of a complete prohibition on cellphone usage while driving to improve traffic safety. These results are expected to provide important insights for future policy-making to cellphone usage while driving.

Although this study has tried to make a thorough analysis of cellphone usage while driving in California, there are still many limitations. First, cellphone usage includes many types, such as texting messages, making phone calls, surfing the Internet, and taking photos, which are very different distracting behaviors. It would be very valuable to analyze the cellphone usage-caused crashes by distraction type to get more details. Second, the effectiveness of any law is greatly influenced by law enforcement, but it is unclear how the ban to the cellphone usage while driving is implemented in practice in California. Considering that law enforcement might be inconsistent over space and time, it is important to identify the role of law enforcement in assessing the effectiveness of the ban. Information of that type would also assist law enforcement agencies in deploying their resources efficiently and equitably. Third, this study does not consider spatial or temporal correlations of crash data in regression analysis, which have been proved to be essential for crash analysis in former studies (Liu et al., 2015; Liu and Sharma, 2017, 2018; Yu et al., 2019). Future studies could consider using spatio-temporal models to analyze the crash data to get more precise findings. Fourth, new features and services have become available on cellphones at an incredibly fast pace in recent years, and the time scale of this analysis spans a considerable amount of technological innovations. Changes in cellphone designs and functions are expected to influence driving behavior. For example, a driver with a smart phone might use the phone in a very different manner from a driver with a non-smart phone. Thus, there is a need for research into the interaction between cellphone development and cellphone usage while driving. The results could provide insights to assist cellphone manufacturers in assuring that phone design minimizes end user risks, or alternatively, supports the addition of functions to suppress cellphone usage while driving. Finally, as a minority crash type, cellphone usage caused-crashes might be very easily influenced by other confounding concurrent events in addition to the ban. Therefore, to produce accurate estimation results as much as possible, future studies might need to take all the possible confounding effects into account in the whole process of experiment design, data collection and data analysis.

Declaration of Competing Interest

The authors declared that there is no conflict of interest.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.tra.2019.04.016.

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