



Impact evaluation of camera enforcement for traffic violations in Cali, Colombia, 2008–2014



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ABSTRACT

Introduction: Cameras for detecting traffic violations have been used as a measure to improve road safety in different countries around the world. In Cali, Colombia, fixed cameras were installed in March 2012 on a number of roads and intersections. All camera devices are capable of detecting simultaneously the following traffic violations: driving over the speed limit, running a red light or stop sign, violation of the traffic ban schedule, and blocking the pedestrian crosswalk.

Objective: To evaluate the impact of camera enforcement of traffic violations in Cali, Colombia.

Methods: A quasi-experimental difference-in-differences study with before and after measurements and a comparison group was conducted. We observed 38 intervention areas and 50 comparison areas (250 m radius), during 42 months before and 34 months after the installation of cameras. Effects were estimated with mixed negative binomial regression models.

Results: In intervention areas, after 12 months, there was a reduction of 19.2% of all crashes and a 24.7% reduction of injury and fatal crashes. In comparison areas, this reduction was 15.0% for all crashes and 20.1% for injury and fatal crashes. After adjusted comparisons, intervention sites outperformed comparison sites with an additional yearly reduction of 5.3% ($p = 0.045$) for all crashes.

Conclusions: The use of cameras for detecting traffic violations seems to have a positive effect on the reduction of crashes in intervention areas. A beneficial spillover effect was found as well in comparison areas; but more evaluations are needed.

1. Introduction

Globally, about 1.25 million people die every year in a fatal road crash, representing a rate of 17.4/100,000 inhabitants. In addition,

approximately 20 to 50 million people suffer non-fatal injuries in such crashes. Worldwide, road crashes are one of the leading causes of death among persons between 15 and 29 years old and they are the ninth cause of death among all age groups. Approximately 90% of these

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fatalities occur in low and middle-income countries, despite that these countries only account for 54% of motor vehicles registered worldwide (World Health Organization, 2015).

In Colombia, deaths due to road crashes are ranked as the second highest cause among deaths due to external causes (Ministerio de Salud y Protección Social, 2016). In Cali, the third largest Colombian city, road crashes are also the second external cause of death (Secretaría de Salud Pública Municipal de Cali, 2016). To illustrate, during 2008–2014, there were 2007 road traffic deaths, which is 287 deaths per year on average, and a mean annual rate of 12.7/100,000 inhabitants; with the lowest rate during 2013 (11.3/100,000 inhabitants) (Observatorio de Seguridad, 2017). In 2017, the most recent year for which data are available, there were 2604 victims who were injured in a road crash (107.6/100,000 inhabitants) and 322 deaths (13.3/100,000 inhabitants), indicating a slightly increase in the mortality rate compared with the 2008–2014 average (Observatorio de Seguridad, 2017; Instituto Nacional de Medicina Legal y Ciencias Forenses, 2018). During 2017 in Colombia, on a national level, mortality rate due to road crashes were higher (13.7/100,000 inhabitants), but the morbidity rate was lower (81.4/100,000 inhabitants) (Instituto Nacional de Medicina Legal y Ciencias Forenses, 2018).

These data illustrate that injuries and deaths caused by road crashes can be considered a public health problem and a growing pandemic (World Health Organization, 2015; Wilson et al., 2010; Bonilla-Escobar and Gutierrez, 2014). In response to this situation, in 2015 the United Nations stated, as the third Objective of Sustainable Development, their goal of a 50% reduction in the number of deaths and injuries caused by road crashes, to be achieved by the year 2020 (World Health Organization, 2017).

Excessive speed is one of the risk factors for road injuries (fatal and nonfatal) as higher speeds come with greater risk of crashing and suffering more severe injuries (World Health Organization, 2015, 2017; Wilson et al., 2010). Therefore, setting and enforcing speed limits has been shown to have a potentially strong impact for the prevention of road injuries and deaths (Wilson et al., 2010; World Health Organization, 2017), particularly on roads with a mixture of different modes of transportation and different types of road users (World Health Organization, 2015). Additionally, the violation of stop signs and red traffic lights at intersections is a concern; see Gomez-Salazar et al. (2017) for a description of this problem in Cali.

Automated camera enforcement using fixed or mobile cameras has been used worldwide to enforce compliance of speed limits and other traffic rules and to improve safety at road intersections. Evaluations of this measure have shown positive effects by reducing red light running and speed violations (Wilson et al., 2010; World Health Organization, 2017; Høye, 2015; Pilkington and Kinra, 2005; Ko et al., 2017; Aeron Thomas and Hess, 2005). Several studies have shown that implementation of photo enforcement significantly reduces the number of crashes (Wilson et al., 2010; World Health Organization, 2017; Høye, 2015; Høye, 2014; Blais and Carnis, 2015; Li and Graham, 2016; Vanlaar et al., 2014), with reductions ranging between 22% and 25.9% for injury crashes (Høye, 2015; Li and Graham, 2016) and 19.7% to 51.0% for crashes with both injuries and deaths (Høye, 2014; Blais and Carnis, 2015). Some studies also show that there can be an increase in rear-end crashes, although these crashes are typically less severe and the increase might only be temporary (Vanlaar et al., 2014).

In Cali, fixed cameras for traffic violations were installed in March 2012. All camera devices are capable of detecting simultaneously the following traffic violations: driving over the speed limit (60 km/h), running through a red light signal, violation of stop signs or other traffic signs, violation of the traffic ban schedule (i.e., driving during non-permitted times as per the vehicle registration based schedule), and blocking the pedestrian crosswalks. The effect of these fixed cameras on the number of road crashes was evaluated previously by González and Prada, in a study a year after the implementation of the intervention (2013) when the first 19 cameras had been installed. They concluded

that there was no significant reduction in the number of road crashes in Cali (González and Prada, 2016). However, the González and Prada study did not account for upstream and downstream traffic in the analysis of data, thereby making it impossible to assess micro-regional effects. Since the completion of this first evaluation, more cameras have been installed in Cali. Today, 40 cameras are located across the city. In addition, more time has elapsed, and more data have become available. As such, the objective of the current study is to evaluate the impact of photo enforcement on the number of crashes with victims (fatal and nonfatal) as well as the total number of crashes (i.e., crashes with victims plus property damage only [PDO] crashes), in Cali between 2008 and 2014. This study is part of the research project “Evaluation of the implementation of photo-detection cameras and their impact on road safety and behavior in Cali, Colombia”, which has been approved by the Ethics Research Board of Universidad del Valle (Cali, Colombia), internal code No. 054-015.

2. Materials and methods

2.1. Context of study

Cali is located in southwestern Colombia at an altitude of 970 m above sea level, with a total area of 561.7 km². The average temperature is 25.5 °C and it has a population of 2,344,734 inhabitants (2014 data) (Departamento Administrativo de Planeación, 2016). Between 2009 and 2014, the average number of registered vehicles was 574,966; among them 66% were private automobiles, 24% were motorcycles and 10% public or special service vehicles (Departamento Administrativo de Planeación, 2016). Since March 2009, Cali has an integrated transportation system based on buses that run on dedicated lanes (Bus of Rapid Transit: BRT) with an operational fleet of 725 vehicles (Departamento Administrativo de Planeación, 2016). Results from a travel demand survey indicate that 37% of inhabitants mainly use private transportation (i.e., passenger vehicle or motorcycle) and 30% use the BRT (Encuesta de percepción ciudadana, 2015).

2.2. Type of study

A quasi-experimental difference-in-differences study design with repeated measurements before and after the intervention at intervention sites and comparison sites was used. An *intervention site* was a site where a camera was installed and defined by means of a buffer with a 250 m radius around the location of the camera. The radius length was based on current knowledge in traffic engineering; specifically, some studies have established this distance as an area of influence (Høye, 2014; Ahmed and Abdel-Aty, 2015). Intervention sites were compared with *comparison sites where no cameras are installed* using buffers with the same radius (250 m). Comparison sites were selected based on road and urban characteristics (please see below) to match them with their respective intervention areas. For each intervention site, two comparison sites were selected and included in the study (or only one where it was not feasible due to the lack of road equivalent sites). A total of 38 cameras were installed in Cali, successively, between 2012 and 2013 (see Fig. 1 and Fig. 2): five in March 2012, five in May 2012, 10 in September 2012, nine in February 2013, five in August 2013, one in September 2013, and three in December 2013. The camera enforcement sites did not have roadway warning signs in their proximity, but it was possible to consult camera locations in the web-page of the Local Traffic Authority of Cali. Two cameras, installed in areas close to the limits of the city in August and September 2013, have no available data for crashes in their surrounding areas; thus, they were not included in the study. Fifty comparison sites were matched with each installed camera according to the traffic flow direction: 20 downstream and 30 upstream (see Fig. 1 for the locations of all observation areas).

Observation areas: Study data correspond to all road crashes, including PDO crashes, injury crashes and fatal crashes, which occurred

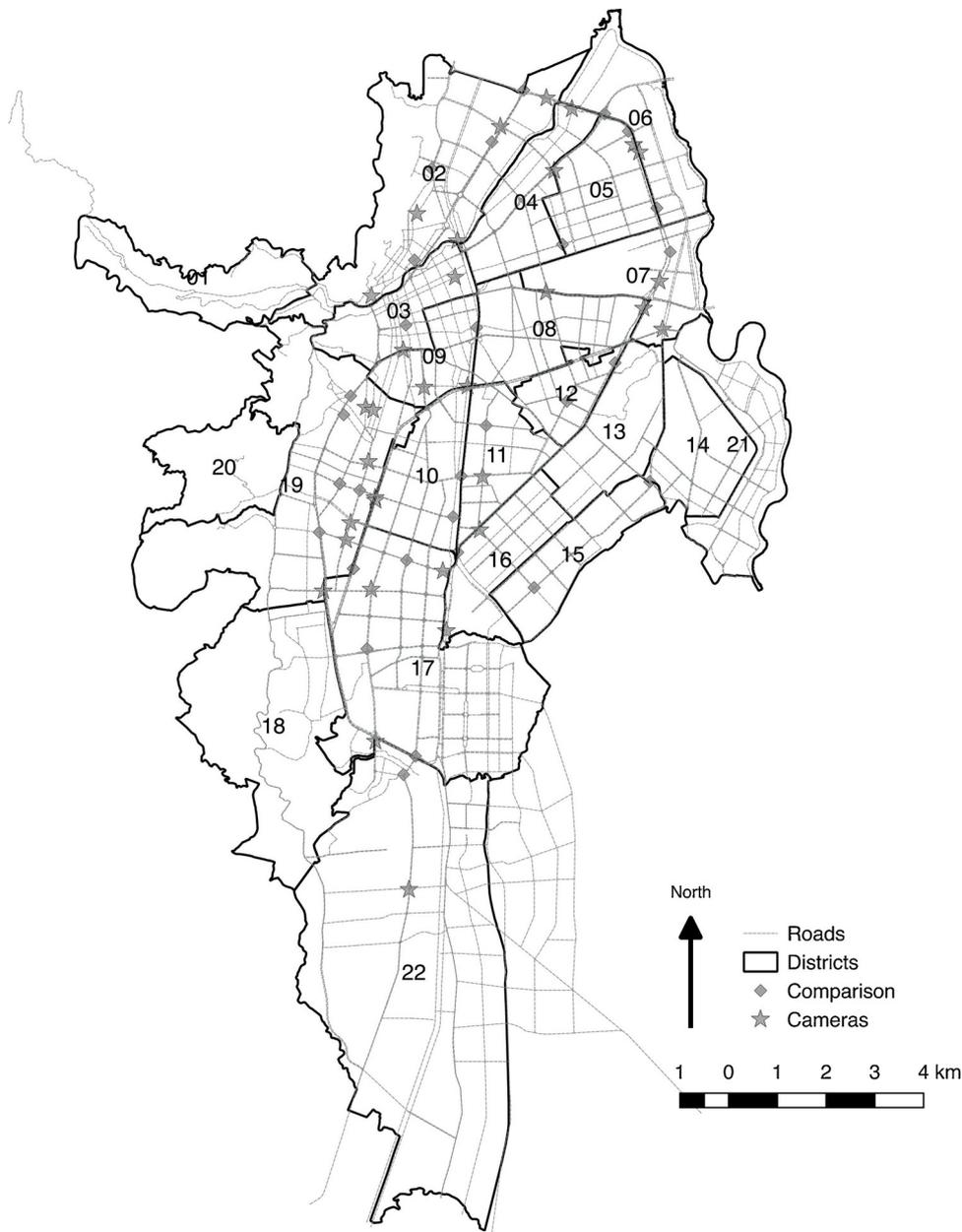


Fig. 1. Location of study observation areas in Cali, Colombia: intervention and comparison sites.

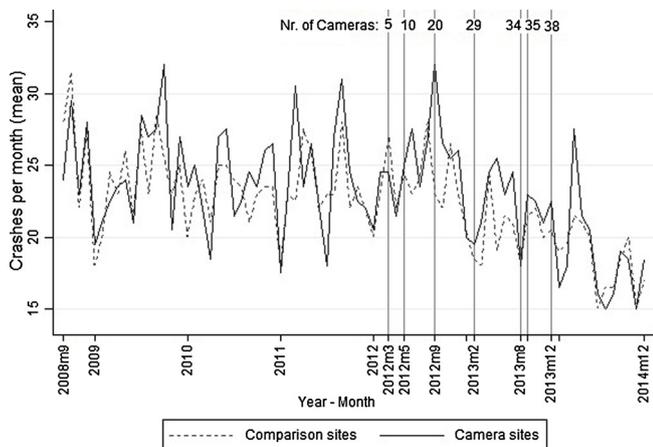


Fig. 2. Trends of mean count for crashes in intervention areas versus comparison areas, between September 2008 and December 2014, in Cali, Colombia.

in the defined study areas, consisting of intervention and comparison locations, between September 2008 and December 2014.

In order to diminish possible selection biases, comparison sites were matched with intervention sites according to road and urban characteristics, using the following matching criteria: (i) road hierarchy, (ii) number of traffic lanes, and (iii) distance between centroids of intervention and comparison sites ranging from 1000 to 2500 m. For cameras located at pedestrian crosswalks, the matching criteria were the type of surrounding land use (residences, commerce, etc.) and speed limit of each area.

2.3. Data sources and data management

Data about crashes in Cali was provided by Programa de Servicios de Tránsito (PST) and Centro de Diagnóstico Automotor del Valle (CDAV), which are companies supporting the operation of traffic technologies in the city, under the purview of the Local Traffic Authority of Cali (in Spanish: Secretaría de Movilidad de Cali) (Bonilla-

Escobar et al., 2016; Osorio-Cuellar et al., 2017). Locations and dates of installation of detection cameras were obtained from reports supplied by PST (Escuela Colombiana de Ingeniería Julio Garavito, 2014). Exact geographic location of each camera was obtained by Google Maps[®]. Each crash in the database was georeferenced with ArcGis[®] 10.2 software and the buffers for study areas were built with the software R-Gui[®]. We observed 38 intervention areas and 50 comparison areas (250 m radius), during 42 months before and 34 months after the installation of the first set of cameras. The study dataset had a balanced panel structure: 88 observation areas with data on the monthly number of crashes in each area over 76 consecutive months, i.e. a time-series per observation area.

2.4. Statistical analysis

Two independent analyses were performed: (i) analysis of monthly counts of all crashes; and (ii) analysis of monthly counts of crashes with injuries and fatalities. Mixed negative binomial regression models (MNBM) with random intercepts were used to analyze the data, structured hierarchically as a panel data set. Random intercepts enabled the modeling of the data structured in three, nested levels: monthly counts of crashes over time (level 1) nested in observation areas at intervention or comparison sites (level 2), nested in clusters consisting of an intervention area matched with its comparison areas (level 3). Incidence Rates Ratios (IRRs) were used as measures of effect, which indicate the monthly relative change (as percentage %) in the number of crashes over time in each observation area, according to its compared characteristics (e.g., intervention sites versus comparison sites). For each IRR, a 95% Confidence Interval (95%CI) was calculated. Also, significance of effects was tested at the 5% level. The data were analyzed with the software Stata[®] 14.1, R-Gui[®] 3.5.0 and MLwiN[®] 3.01 using the library *R2MLwiN* of R-Gui[®]. The regression model was defined as presented in Eq. (1):

$$\begin{aligned}
 \text{Log}(E(Y_{ijk})) = & \beta_{0jk} + \beta_1 t_{ijk} + \beta_2 \text{PosInter}_{ijk} + \beta_3 (\text{PosInter} * t)_{ijk} \\
 & + \beta_4 \text{TypeArea}_{ijk} \\
 & + \beta_5 (\text{TypeArea} * t)_{ijk} + \beta_6 (\text{TypeArea} * \text{PosInter})_{ijk} \\
 & + \beta_7 (\text{TypeArea} * \text{PosInter} * t)_{ijk}
 \end{aligned} \tag{1}$$

where *i* represents month, *j* represents observation area, and *k* represents cluster of observation areas; for one observation area in that cluster, there is a camera and in the others, there is not. Furthermore, *Y* represents the number of crashes at the *j*th observation areas of the *k*th cluster of observation areas in the *i*th month of the time series; *TypeArea* = 0/1 depending on whether or not the *j*th observation area of the *k*th cluster of observation area is a comparison or an intervention site (whether there will be or there will not be a camera there); *PosInter* = 0/1 depending on whether or not the particular month (time) is before or after installation of a camera in the *k*th cluster of observation areas (because detection cameras were installed during different months); and *t* is the month of measurement over a continuous time scale.

A further aspect of the model is the presence of two random effects for the intercept, one defined at the observation area level and the other at the level of observation areas cluster. These random effects take into account, respectively, the unique characteristics of the observation area and the observation areas cluster.

$$\beta_{0jk} = \beta_0 + v_{0k} + u_{0jk},$$

where it is assumed that $v_{0k} \sim N(0, \sigma_{0k}^2)$ and $u_{0jk} \sim N(0, \sigma_{0jk}^2)$.

β_0 and β_1, \dots, β_7 are the fixed parameters. β_0 represents the intercept or baseline level (average) of *Y*. β_1 is the trend or slope of *Y* until the beginning of the intervention in each cluster of areas. β_2 is the immediate effect of the intervention. β_3 represents the difference in trend of *Y* (i.e., it measures the effect of the intervention over time) in the

comparison sites. β_4 indicates the difference in the *Y* intercept between the two types of areas (intervention and comparison) before the intervention. β_5 is the difference in the trend of *Y* between the comparison and intervention sites before the installation of each camera. β_6 indicates the difference in the intercept of *Y* between the types of areas immediately following the installation of each camera. β_7 measures the actual effect of photo enforcement through a comparison of intervention sites for the difference of *Y* trends before and after the interventions (i.e., the difference-in-difference analysis). Additional explanations about this regression model can be found in the electronic supplementary material.

3. Results

3.1. Descriptive analysis

In the study period, there were 168,649 crashes, which took place in the 88 observed areas, 62.1% of which (i.e. 104,699) with injuries or fatalities. Fig. 2 shows a decreasing trend of the mean count of crashes before the installation of the first group of cameras in both time series: intervention areas and comparison areas. Once the first five cameras were installed, an increase in the trend of crashes can be observed, which can be explained by seasonal patterns, in both time series. From the third moment of installation of cameras forward (cumulative number of cameras = 20), the data show there is a rapid decrease in the mean count of crashes in the city, in both time series.

Each vertical line indicates the cumulative number of cameras installed in each moment.

In Table 1, it can be seen that there were statistically significant differences in the median of crashes between the comparison and intervention areas over time and at the pre-intervention period, which disappeared after the intervention. In addition, there were statistically significant differences between pre- and post-intervention periods among types of observation areas.

3.2. Mixed negative binomial model for all crashes

Table 2 shows the estimates obtained by mixed negative binomial regression models using all crashes. A baseline monthly average of 18.52 crashes (intercept in Table 2) was estimated at comparison sites before implementation of cameras (month zero: August 2008; implementation of first cameras: March 2012). When cameras were installed, an increase of 135% (β_2 ; $(2.348 - 1) \times 100$) was estimated when compared with the number of crashes before starting the intervention, independent of the type of observation area; this can be explained by seasonal changes. In areas with cameras, there was an increase of 45% (β_6 ; $(1.452 - 1) \times 100$) compared with comparison

Table 1
Descriptive statistics of monthly counts of crashes in observation areas.

Variable	Median (IQR ^a)	<i>p</i> ^b
<i>Type of area</i>		
Comparison	22 (11–39)	0.013
Camera	23 (11–36)	
<i>Pre-Post Intervention</i>		
Pre	24 (12–39)	< 0.001
Post	20 (10–33)	
<i>Type of area in Pre-Intervention</i>		
Comparison × Pre	24 (12–41)	0.034
Camera × Pre	24 (13–37)	
<i>Type of area in Post Intervention</i>		
Comparison × Post	20 (11–34)	0.135
Camera × Post	20 (9–33)	

^a Interquartile range.

^b Wilcoxon–Mann Whitney test for differences of median of crashes between observation areas or periods.

Table 2
Effects of cameras intervention (areas and periods) and time on monthly counts of all crashes.

Fixed effects	IRR ^a	p	(95%CI)
<i>Main effects:</i>			
Intercept ^b	18.52	< 0.001	13.80–24.85
T (time in months): β_1	0.998	< 0.001	0.997–0.999
Pre-post intervention (i.e., installation of cameras): β_2	2.348	< 0.001	1.882–2.930
Type of area (Intervention vs. Comparison): β_4	0.959	0.825	0.661–1.392
Type area \times Pre-post intervention: β_6	1.452	0.038	1.021–2.067
Type area \times T: β_5	1.001	0.721	0.999–1.002
Pre-post intervention \times T: β_3	0.989	< 0.001	0.986–0.991
Type area \times Pre-Post Intervention \times T: β_7	0.996	0.045	0.991–0.999
Random effects			
Cluster of areas	Variance		
Observation area	0.258		
	0.711		

95%CI: 95% Confidence Interval.

^a Incidence rate ratio = Exponential(β_i).

^b Intercept = estimation of the mean count of crashes at month 0 in comparison areas. Also, see Section 2.4 in the text.

areas when the cameras were installed. During the pre-intervention period, there were no statistically significant differences in monthly crash means between intervention and comparison areas (β_4). From estimates in Table 2, it is possible to estimate the monthly and yearly trends of crash counts, according to types of areas (i.e. comparison vs. intervention), before and after the intervention periods. These trend estimates are shown in Table 3.

During the pre-intervention period, there were statistically significant decreasing trends in the monthly count of all crashes in both intervention and comparison areas. Before the installation of the cameras, there was not a statistically significant difference between types of observation areas for the number of all crashes. During the post-intervention period, these decreasing trends sloped even more, in both intervention and comparison areas (see Table 3), with a more pronounced slope for the intervention areas (IRR = 0.996; 95%CI = 0.990–0.999).

3.3. Mixed negative binomial model for injury and fatal crashes

Table 4 shows the estimates of the mixed model for crashes with injured and fatal victims (i.e. excluding the PDO crashes). A baseline monthly average of 8.3 crashes with victims was estimated in comparison areas before starting the study observations (month zero: August 2008). From estimates in Table 4, it is possible to estimate the monthly and yearly trends of crashes with victims, according to types of areas (i.e. comparison vs. intervention), before and after the

Table 3
Temporal trends of counts of all crashes and crashes with victims.

Periods/areas		Trends Monthly	Trends Yearly
Pre-Intervention periods			
In comparison areas	All crashes	−0.2% (95%CI = −0.1% to −0.3%)	−2.5% (95%CI = −2.0% to −3.7%)
	Crashes with victims	+0.3% (95%CI = +0.2% to +0.4%)	+3.7% (95%CI = +2.6% to +4.9%)
In intervention areas	All crashes	−0.2% (95%CI = −0.1% to −0.3%)	−2.1% (95%CI = −0.7% to −3.6%)
	Crashes with victims	+0.4% (95%CI = +0.3% to +0.6%)	+5.0% (95%CI = +4.1% to +7.0%)
Post-Intervention periods			
In comparison areas	All crashes	−1.4% (95%CI = −1.1% to −1.6%)	−15.0% (95%CI = −12.3% to −17.7%)
	Crashes with victims	−1.6% (95%CI = −1.2% to −1.9%)	−17.1% (95%CI = −13.3% to −20.8%)
In intervention areas	All crashes	−1.8% (95%CI = −1.5% to −2.1%)	−19.2% (95%CI = −16.0% to −22.3%)
	Crashes with victims	−1.9% (95%CI = −1.4% to −2.4%)	−20.5% (95%CI = −15.8% to −24.9%)

Monthly and yearly trends as percentage (%) changes; 95%CI: 95% Confidence Interval.

Table 4
Effects of cameras intervention (areas and periods) and time on monthly counts of traffic crashes with victims (injured or dead).

Fixed effects	IRR ^a	p	(95%CI)
<i>Main effects:</i>			
Intercept ^b	8.30	< 0.001	6.12–11.25
T (time in months): β_1	1.003	< 0.001	1.002–1.004
Pre-post intervention (i.e., installation of cameras): β_2	3.772	0.000	2.745–5.182
Type of area (Intervention vs. Comparison): β_4	0.889	0.510	0.627–1.261
Type area \times Pre-post intervention: β_6	1.460	0.144	0.878–2.427
Type area \times T: β_5	1.001	0.056	1.000–1.003
Pre-post intervention \times T: β_3	0.981	< 0.001	0.978–0.985
Type area \times Pre-Post Intervention \times T: β_7	0.995	0.120	0.989–1.001
Random effects			
Cluster of areas	Variance		
Observation area	0.381		
	0.632		

95%CI: 95% Confidence Interval.

^a Incidence Rate Ratio = Exponential(β_i).

^b Intercept = estimation of the mean count of crashes at month 0 in comparison areas. Also, see Section 2.4 in the text.

intervention periods. These trend estimates are shown in Table 3. During the pre-intervention period, there was a statistically significant increase in the trends of monthly and yearly counts of injury and fatal crashes in both intervention and comparison areas; but these trends were reversed, in both types of areas, when the implementation of cameras started (see Table 3). This decreasing trend in intervention areas was more pronounced than in comparison areas (IRR = 0.996; 95%CI = 0.990–1.002).

In summary, after adjusted comparisons, intervention sites outperformed comparison sites with an additional yearly reduction of 5.3% ($p = 0.045$) for all crashes. However, the specific impact on injuries and fatal crashes was not statistically significant: 5.8% yearly reduction ($p = 0.120$).

4. Discussion

The impact evaluation shows that in Cali, Colombia, camera enforcement for traffic violations significantly reduced all road crashes. There was also a reduction in crashes with victims (i.e. those injured and dead), but this reduction was not significant. To illustrate, while there was a decreasing trend in both intervention and comparison areas after camera installation, in intervention areas this reduction was greater than in comparison areas. For all crashes, the estimated annual reduction was 19.2% in intervention areas with cameras compared with an annual reduction of 15.0% in areas without cameras (significant

difference; $p = 0.045$). For crashes with victims the annual estimated reduction was 20.5% in intervention areas compared with 17.1% in comparison areas (non-significant difference, $p = 0.120$; this lack of significance is discussed below).

There were no significant differences in trends of monthly crashes between intervention and comparison areas in the period before the installations of cameras. This supports the selection of comparison areas in this study given that their behavior, in terms of crashes, was similar to the intervention areas before the installation of the cameras (Parascandola and Weed, 2001; Gertler et al., 2017). Moreover, the current evaluation has shown an ongoing decreasing trend in the number of crashes between 12 and 21 months after the installation of the cameras. This finding is consistent with the Norwegian study showing that effect of cameras continued three years after the installation of the first set (Høye, 2015).

The effectiveness of cameras on the reduction of crashes in Cali is consistent with findings from other studies using the same quasi-experimental approach (before-after and comparison group), although no study evaluated cameras while controlling several traffic infractions at the same time. In this manner, it was found that *speed cameras* yield reductions between 5–69% for crashes, 12–65% for injuries and 17–71% for deaths (Pilkington and Kinra, 2005; Høye, 2014). On the other hand, the presence of *red-light running cameras* can lead to reductions between 15% to 37% in all types of crashes and 16% reduction in crashes with victims after installing those cameras (Ko et al., 2017; Aeron Thomas and Hess, 2005; Vanlaar et al., 2014; Ahmed and Abdel-Aty, 2015); although specifically the rear-end crashes could increase in some settings (Ko et al., 2017).

In this study, the buffer of intervention areas included road sections with a 250 m radius around the location of each camera. Høye's review also found a reduction of 18% in the number of crashes in locations at 250 meters from the speed camera's point of installation (Høye, 2014). Nonetheless, in a Norwegian study with short distances (i.e. 100 m) before and after camera locations, findings did not show significant reductions in crashes with injured or dead victims, but authors argued that an underestimation of effect could be the result of the low number for crashes with victims (Høye, 2015). Thus, the definition of intervention areas using buffers of radius of 250 m seems appropriate in light of the evidence (Høye, 2014).

Additionally, this study found a “spillover or halo effect” in the micro-region close to the point of installation of each camera. Comparison areas were located, on average, 1500 m from camera locations. The reductions in crashes with victims and all crashes, after the installation of cameras, were also significant in these comparison areas, but the reduction was lower than in intervention areas. Our data suggest that, in Cali, the presence of cameras could have led to drivers adopting better road behaviors in the micro-regions surrounding cameras. Other studies have shown a significant halo effect (on reduction of crashes) of speed and red light cameras in locations without, but close to, the cameras (Høye, 2014; Vanlaar et al., 2014; Ministerio de Salud y Protección Social, 2016); but this effect diminishes as the distance from installed cameras increases (Høye, 2015; Høye, 2014). Thus, such a spillover effect is expected when sections without cameras are used as a comparison group. This could help to explain the lack of a significant difference in reductions in crashes with victims between intervention and comparison sites in the current and other studies (Høye, 2014; Vanlaar et al., 2014).

Furthermore, our approach to the measurement of the spillover effect (β_3) was statistically significant, in such a way that in the comparison sites we can see average effects in the trend, almost equivalent to the trend effects before the interventions in the same comparison areas; in the case of all accidents, IRRs were: $\beta_1 = 0.998$ ($p < 0.001$) and $\beta_3 = 0.989$ ($p < 0.001$). Although a timid educational campaign was promoted in Cali prior to the installation of the cameras, it is likely that β_3 estimate will partly capture these spillover effects found on the comparison areas. Precisely, the Ministry of Transportation of Colombia

recently regulated the operation of photo-detection devices through the Resolution 718 (March 2018) which dictates to the operators to inform drivers about the proximity of electronic detection cameras using roadway warning signs; but such signs were not present at the moment of the current evaluation (2012–2014). Thus, before the year 2018, some drivers could have had exact information about the locations of detection cameras (e.g. taxi-cab drivers and some users of GPS navigation systems), but the use of such technologies were not frequent among drivers in the city.

The control, estimation and explanation of spillover effects suggests future directions of research to the extent that both advertising and diffusion campaigns of cameras, as well as the lack of knowledge of their exact locations, undoubtedly explain in a large proportion the presence of these spillover effects (Jiang and Ouyang, 2017). Moreover, the number of traffic violations detected by the cameras increased during the evaluation period (2012–2014), according to the CDAV/PST registers (data not shown), which would discard drivers' learning behavior hypothesis, and also, it could help to explain the spillover findings.

In the Colombian context, a similar evaluation was done in Medellín: micro-region effects were taken into account in a radius of 200 m around locations of cameras and comparison areas, with similar traffic and crash occurrence. That study shows a 10.1% reduction in the number of crashes after the cameras intervention according to the difference-in-differences approach (Restrepo, 2014). On the other hand, the previous evaluation of traffic violations detection cameras in Cali did not identify any effect on the overall reduction of crashes in the city (González and Prada, 2016). However, results did indicate that when the cameras were installed there was an estimated increase in all crashes at the intervention intersections compared to comparison intersections. As previously mentioned, the lack of effect of cameras on reductions in crashes by González and Prada study could be explained by the short time between installation and evaluation of cameras, the narrower coverage of the intervention and because of the spill-over effect found in the current study.

Despite the reported evidence on the effectiveness of automated traffic enforcement, such as speed surveillance cameras or red light cameras at intersections, this type of road safety measure can be controversial and often faces political challenges. Common criticism is that they are merely meant to generate revenue, rather than to protect the public, mainly in relation to speed enforcement cameras (Høye, 2014; Tay, 2010; Maisel, 2013). In Colombia, this was not any different: local newspapers discussed the legality of installation of cameras and criticized their alleged purpose of generating revenue (El Tiempo, 2016a, 2016b; El País, 2012). In addition, before July 2017, there was no law to regulate the proper installation and operation of these devices, which was ultimately achieved when enacting the National Law 1843 in 2017.

This study has some limitations including: (1) it was not possible to analyze sub-types of crashes (e.g. right-angle crashes versus rear-end crashes) due to lack of detailed data (some studies have found different effects depending on the type of crash; see for example Vanlaar et al., 2014). (2) There were no details available about specific traffic violations and specific types of cameras (e.g. only speed infractions) because the cameras in Cali focused on all infractions at the same time. (3) Analyses were made at a micro-level because it was not a comparison with other urban settings, which could detect macro-effects of camera interventions (Høye, 2015; Høye, 2014; Vanlaar et al., 2014). (4) An over-estimation of the effect of detection cameras may occur when volume of traffic moves toward adjacent roads which do not have these devices (Høye, 2014). However, this study did not explore changes in traffic flow in observation areas, nor changing traffic flow in adjacent roads, nor the number of crashes on adjacent roads. Nonetheless, due to the limited road infrastructure in the city, drivers have limited alternatives for avoiding cameras. Additionally, the matching criterion of Annual Average Daily Traffic (AADT), which is related to the occurrence of crashes (Dickerson et al., 2000), was not available for the

entire road network of Cali, thus it was not used in this study. The AADT, being the number of vehicles passing through a given cross section in a day based on annual data, is often used to classify urban roads. Nonetheless, traffic flow depends on characteristics of the road design (Dickerson et al., 2000); which, indeed, was a matching criterion in our study. In this regard, when selecting comparison sites located in urban areas with similar hierarchies, one could argue that indirectly the AADT is being considered in our study (Hong et al., 2005; Durantón and Turner, 2011). (5) It was a short period (12 months) after the installation of the last cameras, thus, future studies are warranted in order to explore drivers' learning behaviors after a longer intervention period in the city. (6) Spillover effects of cameras were tested only in a range between 1500 and 2500 m, due to the study design constraints; thus, it is necessary to testing different distances in future studies. (7) Finally, it is necessary to recognize that the results obtained in the impact evaluation of photo-detection enforcement in Cali, Colombia, are very sensitive to the methods used. The literature on road safety indicates that in addition to the difficulties of controlling for regression to the mean in zones and intersections of high accident rates, there are also masked effects that come from difficulties of controlling for the effects of spillover in the comparison areas, as it is the case of our study (Elvik et al., 2009). Nonetheless, according to the results of the estimations, the parameters of intervention vs. comparison (β_4), as well as that of area type (β_5), were not statistically different from zero, which guarantees a similar risk of accident between the two types of areas (intervention and comparison).

On the other hand, the current study has several strengths: (1) it considered random effects that account for unmeasured differences that may exist between different areas of observation, as well as inclusion of temporary effects that allowed considering different factors changing over time in the city. These effects could influence the occurrence of crashes, such as other initiatives for road safety like enforcement sobriety checkpoints (Bonilla-Escobar et al., 2016), the behavior of drivers and pedestrians, or the number of registered vehicles (Pilkington and Kinra, 2005). (2) A methodological advantage was a micro-region approach which allows for inclusion of different moments of installation of cameras by means of a random effect of time. (3) When considering a comparison group, confounding effects were controlled by means of matching variables, such as traffic flow, road infrastructure characteristics, road safety signs and type of land use in urban areas. However, there is no consensus on the criteria for choosing comparison groups in road safety research (Pilkington and Kinra, 2005; González and Prada, 2016; Perez et al., 2007; Novoa et al., 2010). (4) Traffic violation cameras are generally installed in areas with high incidence of crashes (Høye, 2015), and this may produce “regression to the mean” which results in an overestimation of cameras effect, because in these locations the number of crashes can be expected to decrease and “regress to the mean”, even in the absence of any intervention (Aeron Thomas and Hess, 2005). However, this effect was partially controlled in the current study because we have a data set consisting of time series for monthly counts of traffic incidents spread out over several years before and after the implementation of the safety measure. As such, the phenomenon of regression to the mean can be modeled, and therefore, better controlled in the analyses (Vanlaar et al., 2014; Brown and Prescott, 2014).

5. Conclusions

The implementation of a photo enforcement road safety program with fixed cameras for detection of traffic violations in Cali, Colombia was related with a significant reduction in all crashes in interventions areas; although the crashes also diminished in the comparison areas. While the effect on injury crashes found in this study was not significant, the data suggest this may be the result of a stronger spillover effect from areas with cameras to areas without cameras. This possible explanation will be further investigated in future evaluations, taking

into account cameras spillover effects with longer distances or drivers' learning behaviors over time. Other ways to strengthen the research design in future evaluations include exploring macro-city effects and distinguishing between different types of crashes. Despite these limitations, findings from our study show that when cameras for detection of traffic violations are installed in the most problematic areas, they contribute positively to the road safety of urban areas. Furthermore, our results help to mitigate the controversy surrounding cameras because the data demonstrate that these cameras contribute to making roads safer, rather than merely generate revenue. Finally, our study is valuable in light of the lack of evidence for this type of road safety measures in Latin American cities, which have different road characteristics, social and environmental conditions in comparison with cities in high-income countries where these interventions have typically been evaluated.

Conflict of interest

The authors declare no conflict of interest.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at <https://doi.org/10.1016/j.aap.2019.02.002>.

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