J Urban Health
https://doi.org/10.1007/s11524-021-00515-4

Impact of ShotSpotter Technology on Firearm Homicides and Arrests Among Large Metropolitan Counties: a Longitudinal Analysis, 1999–2016

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Accepted: 8 January 2021

Abstract Over the past decade, large urban counties have implemented ShotSpotter, a gun fire detection technology, across the USA. It uses acoustic listening devices to identify discharged firearms' locations. We examined the effect of ShotSpotter with a pooled, cross-sectional time-series analysis within the 68 large metropolitan counties in the USA from 1999 to 2016. We identified ShotSpotter implementation years through publicly available media. We used a Poisson distribution to model the impact of ShotSpotter on firearm homicides, murder arrests, and weapons arrests. ShotSpotter did not display protective effects for all outcomes. Counties in states with permit-to-purchase firearm laws saw a 15% reduction in firearm homicide incidence rates; counties in states with right-to-carry laws saw a 21% increase in firearm homicide incidence rates. Results suggest that implementing ShotSpotter technology has no significant impact on firearm-related homicides or arrest outcomes. Policy solutions may represent a more cost-effective measure to reduce urban firearm violence.

Keywords Injury prevention · Firearm violence · Urban crime · Gunshot detection technology

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Introduction

Gun violence in the USA is a public health problem that disproportionately affects young people of color living in urban communities. Firearm homicides tend to concentrate in large metropolitan areas [1]. In 2018, 12,357 (88.5%) of all firearm homicides took place in a metropolitan county [2]. That same year, non-Hispanic blacks ages 15 to 34 years accounted for 62.2% of those intentionally killed despite comprising only 14.8% of the population.

In the USA, the total lifetime cost of homicides, including medical expenses and lost economic productivity, is estimated to be $25.1 billion [3]. Homicides only scratch the surface of the larger public health issue of firearm violence. It is estimated that for every firearm

Published online: 30 April 2021

death (including suicides), there are at least two more persons non-fatally injured from gunshot wounds, or approximately 73,330 people annually [4]. When the cost of firearm injury is added to the lifetime cost of homicides, the total annual cost of gun violence in America approaches $229 billion [5]. The significant cost of gun violence, in both lives lost and dollars spent, makes it a costly and persistent US public health crisis.

One of the major barriers in reducing urban firearm violence is the significant underreporting of shots fired [6]. It is estimated that on average, only 20% of shootings are reported to law enforcement [7]. A recent attempt to address this issue is the deployment of ShotSpotter, which is the most commonly used gunshot detection technology (GDT), or acoustic firearm detection system [8]. ShotSpotter [9, 10] is used by law enforcement departments in over 100 US cities and several locations abroad [9]. This technology provides law enforcement with an alternate reporting mechanism that mitigates underreporting issues and provides more accurate shooting location information [11]

GDT uses acoustic sensors to detect noise with similar features to that of a firearm discharge [6, 10, 12, 13]. ShotSpotter sensors, placed to provide sound coverage over large outdoor spaces, have a range of 1200 feet and filter ambient noise to detect firearm discharges. When a suspected firearm discharge occurs, sensors activate the ShotSpotter software, which alerts a centralized repository, wherein acoustic experts make a determination of the likelihood that the activation was due to gunfire and not a similar sound like the backfiring of a motor vehicle. If a firearm discharge is confirmed, the local end user, typically a law enforcement agency (LEA), is notified. The process of firearm discharge to law enforcement notification takes approximately 60 seconds to complete [10]. ShotSpotter's firearm discharge identification fidelity is high [6]. A 2006 field study by the National Institute of Justice found that the technology detected 99.6% of 234 firearm discharges in 23 locations [6, 10]. After an initial setup charge of $10,000 per square mile (PSM) covered, ShotSpotter fees range from $65,000 to $90,000 PSM/year [14]. For example, in a given year, ShotSpotter technology can cost the city of Hartford, CT, between $730,000 and $1 million for 11.25 mi^2 of coverage [15].

The literature evaluating GDT is fairly limited. An early investigation into the impact of GDT on Dallas Police Department officer response times and workload found a 7% reduction in officer response times but reported a significant increase in responding officer workload and more time required to respond to gunshot service calls [13]. Mares and Blackburn (2012) examined the effectiveness of GDT in reducing gun-related crime in St. Louis, MO. Specifically, they assess the impact on reported "shots fired' and gun crimes. They found the implementation of GDT in St. Louis, MO, to be somewhat related to a drop in citizen reports of "shots fired" but did not find GDT to impact the level of reported gun crimes [16]. Similarly, in Philadelphia, PA, Ratcliffe et al. (2019) found that although GDT increased police awareness of shooting incidents by a dramatic 259%, this did not translate to founded incidents [17]. They also reported that false positive calls influenced officers' responsiveness to GDT activations. Using data collected from the police dispatch log of a southeastern Massachusetts City, researchers evaluated the impact of ShotSpotter on the effective identification, investigation, and prosecution of "gun-involved" crimes [11], finding that ShotSpotter improved police response and dispatch times, but did not improve case closures. Lastly, a qualitative study by Lawrence et al. (2018) found that police and community stakeholders view GDT as a tool to generate information valuable to investigation of gun-involved crimes [12].

Other research have explored the impact of GDT on gunshot victims' healthcare-related outcomes. Three site-specific studies evaluate ShotSpotter technology activations on first responder transport times and patient outcomes. A study of Camden, NJ's ShotSpotter found that the technology led to decreased response times of police and emergency medical services (EMS), but no differences in patient outcomes [10]. Similarly, the study in Oakland, CA, demonstrated reduced prehospital times [6]. However, a replication of these ShotSpotter evaluations in Hartford, CT, found no difference in EMS response times, transport times, or patient outcomes. These differences in findings may be attributed to local policies. For example, Camden police are allowed to transport victims to the hospital in their vehicles, whereas Hartford police rely on EMS to transport victims.

Previous research has identified that large metropolitan county-level firearm violence is impacted by state firearm laws [18]. Researchers using data from 1984 to 2015 examined the impact of various state firearm laws on county-level firearm homicides. Among metropolitan counties, permit-to-purchase (PTP) laws were associated with a 14% reduction in firearm homicides; right-to-carry (RTC) laws were associated with a 4% increase in firearm homicides; stand your ground (SYG) laws were associated with a 7% increase in firearm violence; and violent misdemeanor prohibitions (VM) were associated with 14% increase in firearm violence over the study period [18]. PTP laws go beyond mandating background checks for sale of firearms from federally licensed firearms dealers and add additional handgun purchaser requirements [19, 20]. RTC laws remove law enforcement discretion over who is legally allowed to carry a concealed handgun in public or allow for permitless carry of handguns [18, 21, 22]. SYG laws provide individuals legal protection in the use of deadly force when a situation contains a perceived threat through the elimination of the duty to retreat [18, 23]. VM laws prohibit those convicted of a misdemeanor violent crime from purchasing firearms [24, 25]. Our study seeks to understand the independent effect of ShotSpotter while simultaneously controlling for the state-level policy context.

The literature demonstrates that ShotSpotter is a powerful surveillance tool with potential for assisting LEA. However, scholars fail to adequately evaluate the impact of ShotSpotter on arrest outcomes or on the long-term trajectory of homicide rates. Other assessments of ShotSpotter, available through the company's website, purport an increase in arrests, reductions in violence, and increase in seized weapons after ShotSpotter implementation [26], but these studies, not peer-reviewed, are based on anecdotal media reports. There is currently a lack of robust, peer-reviewed research that examines the impact of GDT in general, or ShotSpotter technology specifically, on rates of nationwide firearm violence and arrests related to firearm crimes. In fact, such evaluations have been hindered due to the proprietary nature of the data collected by ShotSpotter [27]. Given the associated costs and proliferation of ShotSpotter technology throughout the USA, there is a need to understand its overall impact as a deterrent for firearm homicides or as a tool for law enforcement to improve arrest rates.

Methods

In order to examine the effect of implementing ShotSpotter technology on firearm violence and law enforcement arrests, we conducted a pooled, cross-sectional time-series analysis from 1999 to 2016. Our panel includes 68 large metropolitan counties in the USA. We employed a generalized linear model with a Poisson distribution to model the association between implementing ShotSpotter and [1] firearm homicides, [2] murder arrests, [3] weapons arrests. All three outcomes were indexed at the county-year level.

Data and Variables

Given the nature of ShotSpotter technology, and information from the ShotSpotter website, we hypothesized that implementation of ShotSpotter would reduce firearm homicides as well as increase arrests related to firearm crimes. Thus, the primary outcomes for this study were county-level counts of firearm homicides, murder arrests, and weapons arrests. We obtained counts of firearm homicides from the Centers for Disease Control and Prevention's Wide-ranging Online Data for Epidemiology Research (WONDER) system. We obtained murder- and weapons-related arrest information from the Uniform Crime Reporting (UCR) Program Data: County-Level Detailed Arrest and Offense Data. UCR data was obtained through the Inter-university Consortium for Political and Social Research [28]. As ShotSpotter technology has been implemented in densely populated urban areas, we restricted our analysis to counties with US Census Urbanization codes of large central metropolitan.[1] Importantly, we were unable to use the exact geographic coverage area of ShotSpotter technology as our unit of analysis for implementing counties as this information is not publicly available. The potential limitations of this decision are discussed later. The study contained 68 counties for 18 years, a total of 1224 county-year observations. Of note, murder and weapons arrests were not available for Florida counties for each year of the study period. Additionally, murder and weapons arrest rates were not available in 2015 in each county and were thus linearly interpolated.[2]

We attempted to ascertain ShotSpotter implementation dates via the ShotSpotter website; however, while the website lists the areas where the technology is currently deployed, it does not state the date of the technology's deployment [30]. Thus, we searched publicly available news media through ProQuest and Google to identify each

[1] Large central metropolitan counties are defined as "…counties in MSA of 1 million population that: 1) contain the entire population of the largest principal city of the MSA, or 2) are completely contained within the largest principal city of the MSA, or 3) contain at least 250,000 residents of any principal city in the MSA." [29]

[2] We also ran the analysis without interpolated values, and the results are the same.

county's deployment year. For each county that ShotSpotter listed as currently deploying technology for, we searched the following: "[County name] ShotSpotter," and "[County name] ShotSpotter implementation." We created an indicator variable for the presence of ShotSpotter, where "0" equaled no technology deployed, and "1" equaled technology deployed. We emailed ShotSpotter on April 15, 2020, to ascertain definitive implementation dates, but they did not reply.

We also used WONDER to access county-level variables, including percentage of the population who were African American, male, ages 15–24 years, and county population. We accessed county-level unemployment rates through the Bureau of Labor Statistics Local Area Unemployment Statistics. We accessed county-level percentage of poverty from the US Census Bureau's Small Area Income and Poverty Estimates (SAIPE) program, which produces single-year estimates of poverty for US counties from 2009 to 2016 [31]. We accessed county-level poverty rates from the 2000 census and interpolated poverty rate in 1999 and from 2001 to 2008 linearly.

We used the Centers for Disease Control and Prevention's Web-based Inquiry Statistics Query and Reporting System (WISQARS) to identify the state-level variable of household firearm availability [2]. This constructed variable is a ratio of firearm suicides to total suicides and state-year indexed and is a validated proxy measure for the percentage of houses that own firearms [18, 19, 19, 21, 22, 32]. We used the US Census Bureau's Annual Survey of State and Local Government Finances to obtain state-level law enforcement expenditure.

We conducted legal research and used existing evidence to identify the effective dates for the following state firearm laws that have previously shown a relationship to firearm homicides at the county level: RTC laws, PTP laws, SYG laws SYG, and VM laws [33]. We checked our legal research against preexisting literature. We coded laws "0" when absent, and "1," when present, and we coded the law variables as a decimal, representing the number of months the law was in effect, during the year of the law's passage.

Analysis

We conducted a pooled, cross-sectional time-series analysis to evaluate whether ShotSpotter technology affected firearm homicides, murder arrests, and weapons arrests. We used a generalized linear model specifying a Poisson distribution. We used the log transformed county-level population to serve as our population offset, interpreting results as incidence rate ratios (IRR). We included county and time fixed effects, so the IRR should be interpreted as the average difference in the incidence of an outcome in a county with ShotSpotter technology compared with a county without ShotSpotter technology. We clustered our standard errors at the county level to account for variance within each county and correct for overdispersion in a Poisson model. Additionally, we weighted our models by the county population to improve the model's precision and assess heterogeneous treatment effects [34].

We also assessed ShotSpotter's effect on our outcome variables using leads and lags. Lag models act as a sensitivity analysis, testing whether the effect of ShotSpotter was experienced 1 or 2 years after its initial implementation. It may take time for ShotSpotter technology to be implemented—law enforcement officers need time to adjust police practices, and anecdotal evidence suggests some cities increased ShotSpotter technology coverage after a small trial phase.

Lead models act as a placebo test, examining if there were increases or decreases in violence 1 and 2 years prior to the implementation of ShotSpotter. One- and two-year lead models were created to test whether the results found were due to possible reverse causality. For example, if counties that experienced increased firearm homicide violence elected to purchase ShotSpotter technology.

Additionally, we assessed whether outcome missingness biased our outcome. We accomplished this by removing all missing outcome data and running each model to compare beta coefficients. Our outcome measures (and therefore sample) ends in 2016, but some counties adopted ShotSpotter after 2016. To address potential policy endogeneity, we refined our comparison counties to only include counties that adopted ShotSpotter technology after 2016, or treatment counties remain the same—those adopting before 2016—and we dropped counties who have still never adopted ShotSpotter. All analyses was conducted using Stata Version 15.0 [35].

Results

Figure 1 displays the trends of firearm homicides per 100,000 population within large metropolitan counties in the USA from 1999 to 2016 overall and by implementation status. Overall, counties that implemented ShotSpotter had above average firearm homicide rates, whereas counties that never implemented ShotSpotter

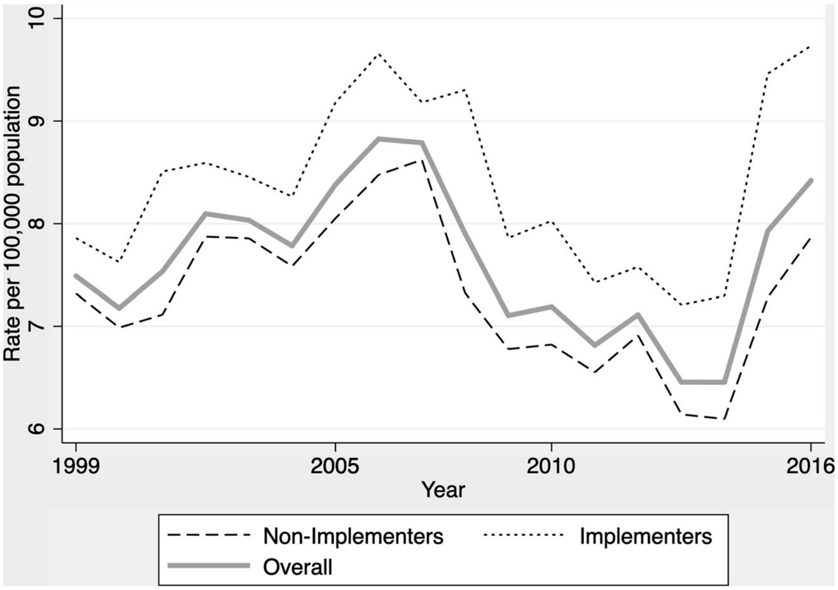

Fig. 1 Firearm homicide rates among large metropolitan counties by ShotSpotter Implementation Status, 1999–2016

had below average firearm homicide rates. Figure 2 displays the trends of murder arrests and weapons arrests per 100,000 population. Both murder arrest rates and weapons arrest rates have reduced in recent years with counties that never implemented ShotSpotter and counties that implemented ShotSpotter hovering around the national average for both outcomes.

Table 1 displays included counties, states, county FIPS codes, average number of firearm homicides, and presence of ShotSpotter. According to the ShotSpotter website, a total of 26 large metropolitan counties have deployed ShotSpotter; however, only 18 of the 26 did so within the study period. Several states have more than one large metropolitan county that has deployed ShotSpotter. California has the most counties in which ShotSpotter was implemented (Alameda, Sacramento, San Diego, San Francisco counties).

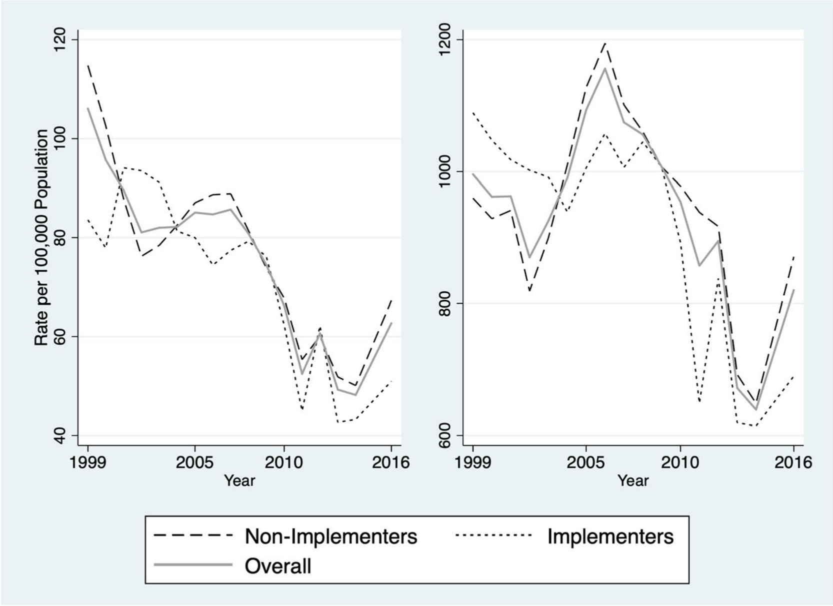

Fig. 2 Murder and weapons arrest rates per 100,00 population among large metropolitan counties, by ShotSpotter Implementation Status 1999-2016

Table 1 Large central metropolitan counties and ShotSpotter implementation

County	State	ShotSpotter implementation year (citation)	County Fips	Average firearm homicide (rate per 100,000)
Jefferson County	AL	2010 [39]	01073	13.68
Maricopa County	AZ	2009	04013	5.68
Alameda County	CA	2006 [40]	06001	6.86
Los Angeles County	CA		06037	6.63
Orange County	CA		06059	1.53
Riverside County	CA		06065	3.21
Sacramento County	CA	2015 [41]	06067	4.32
San Diego County	CA	2016 [42]	06073	1.87
San Francisco County	CA	2008 [43]	06075	4.51
Santa Clara County	CA		06085	1.42
Denver County	CO	2015 [12]	08031	4.96
Hartford County	CT	2012 [44]	09003	2.88
District of Columbia	DC	2006 [45]	11001	19.34
Duval County	FL	2017* [46]	12031	9.34
Hillsborough County	FL	2015 [47]	12057	3.53
Miami-Dade County	FL	2013 [48]	12086	6.77
Orange County	FL		12095	5.30
Pinellas County	FL		12103	2.96
Fulton County	GA	2018* [49]	13121	10.82
Cook County	IL	2012 [50]	17031	9.73
Marion County	IN		18097	10.43
Jefferson County	KY	2017* [46]	21111	6.64
Orleans Parish	LA		22071	41.00
Baltimore city	MD	2018* [51]	24510	29.18
Suffolk County	MA	2007 [52]	25025	5.53
Kent County	MI		26081	2.25
Wayne County	MI		26163	16.66
Hennepin County	MN	2007 [53]	27053	3.01
Ramsey County	MN		27123	2.57
Jackson County	MO	2012	29095	12.63
St. Louis city	MO	2017* [47]	29510	26.96
Clark County	NV	2017* [56]	32003	5.16
Essex County	NJ	2008 [57]	34013	12.07
Hudson County	NJ		34017	2.76
Union County	NJ		34039	3.33
Bronx County	NY		36005	6.11
Erie County	NY		36029	4.20
Kings County	NY		36047	5.49
Monroe County	NY		36055	4.19
New York County	NY		36061	2.31
Queens County	NY		36081	2.42
Richmond County	NY		36085	2.56
Mecklenburg County	NC		37119	6.63
Wake County	NC		37183	2.35

Table 1 (continued)

County	State	ShotSpotter implementation year (citation)	County Fips	Average firearm homicide (rate per 100,000)
Cuyahoga County	OH		39035	6.03
Franklin County	OH	2019* [58]	39049	6.32
Hamilton County	OH	2017* [47]	39061	7.13
Oklahoma County	OK		40109	6.09
Multnomah County	OR		41051	2.31
Allegheny County	PA	2015 [16]	42003	5.97
Philadelphia County	PA		42101	16.92
Providence County	RI		44007	2.53
Davidson County	TN		47037	8.56
Shelby County	TN		47157	13.59
Bexar County	TX		48029	4.71
Collin County	TX		48085	1.79
Dallas County	TX		48113	7.07
Harris County	TX		48201	7.01
Tarrant County	TX		48439	3.56
Travis County	TX		48453	1.83
Salt Lake County	UT		49035	1.77
Arlington County	VA		51013	---**
Alexandria City	VA		51510	---**
Norfolk City	VA		51710	10.30
Richmond City	VA		51760	21.33
Virginia City	VA		51810	3.31
King County	WA		53033	1.99
Milwaukee County	WI	2011 [12]	55079	9.32
Adopters (No. in study)		26 (18)		

Note: ShotSpotter implementation dates based on publicly available information. States with asterisks have ShotSpotter implementation dates that fall outside the study period thus were not included in the analysis. *Indicates counties where ShotSpotter was implemented during study period. **Arlington and Alexandria City had zero or surprised homicide values for the majority of study years

Table 2 displays the results of the three outcome models. None of the three primary outcomes displayed a significant relationship with the presence of ShotSpotter (firearm homicides incidence rate ratio (IRR) = 1.035; 95% confidence interval (CI) 0.84, 1.27; murder arrest IRR = 0.993, 95% CI 0.73, 1.36; weapons arrest IRR = 0.929, 95% CI 0.75, 1.15). Controlling for the presence of ShotSpotter technology and other covariates, large metropolitan counties in states with PTP laws had 15.7% lower firearm homicide incidence. while counties in states with RTC laws had 23.3% (95% CI 1.09, 1.39) increased firearm homicide incidence compared with counties in states without such laws.

Figures 3, 4, and 5 provide the lead and lag model coefficient and 95% confidence intervals for the effect of ShotSpotter technology on the three outcome models. Lead and lag models for the presence of ShotSpotter technology displayed similar non-associations with firearm homicides, murder arrests, and weapons arrests. When the implementation year of ShotSpotter technology is altered, there was no significant change in its relationship to firearm homicides and arrests. Other model checks suggest that our primary model is robust. Removing counties with missing data did not alter IRR or standard error within the primary model. Analysis among counties that ever-adopted ShotSpotter did not

Table 2 Impact of ShotSpotter technology on firearm homicides, murder arrests, and weapons arrests among large metropolitan counties in the USA, 1999–2016

Covariates	Firearm homicides			Murder arrests			Weapons arrest		
	Incidence rate ratio (IRR)	95% CI: lower	95% CI: upper	IRR	95% CI: lower	95% CI: upper	IRR	95% CI: lower	95% CI: upper
ShotSpotter	1.035	0.84	1.27	0.993	0.73	1.36	0.929	0.75	1.15
Firearm laws									
Right-to-carry	1.214	1.05	1.41	0.489	0.27	0.88	0.750	0.52	1.08
Permit-to-purchase	0.843	0.72	0.99	0.507	0.23	1.14	0.872	0.54	1.40
Violent misdemeanor prohibitions	1.107	0.98	1.24	1.260	1.02	1.58	1.033	0.88	1.22
Stand your ground	1.060	0.95	1.19	0.885	0.64	1.22	0.995	0.87	1.14

Significance assessed at $p < 0.05$. Covariates with significant associations are italicized. Northeast used as reference in region. Each model contains year fixed effects and random intercept terms for firearm homicides at the county and state level. We employed robust estimators of variance, clustered at the county level

alter IRR. Weighted models by population did not alter IRR and standard errors within the primary model.

Discussion

To our knowledge, this is the first examination of the impact of ShotSpotter technology on county-level firearm violence and arrests. We found no difference in county-level homicides, murder arrests, and weapons arrests for large metropolitan counties with and without ShotSpotter technology, controlling for various county- and state-level demographics as well as state firearm laws. Our sensitivity models strengthen the argument for our finding of no-association.

ShotSpotter is advertised as a means to reduce urban firearm violence; therefore, the potential for reverse causality is high. Unlike public policies that take time and political will to implement, ShotSpotter is available for purchase, and its implementation is dictated by a municipality's willingness to pay. As such, a municipality may choose to implement ShotSpotter if they experience an unusual upward trend in firearm violence. Our insignificant findings within the 1- and 2-year lead models suggest that firearm homicides in counties that adopted ShotSpotter did not experience higher incidence rates of fatal firearm violence 1 and 2 years prior to the actual year of ShotSpotter implementation, reducing the likelihood of reverse causality. ShotSpotter, like any new policy or program intervention, is subject to a lag from the time of implementation to the time of effect.

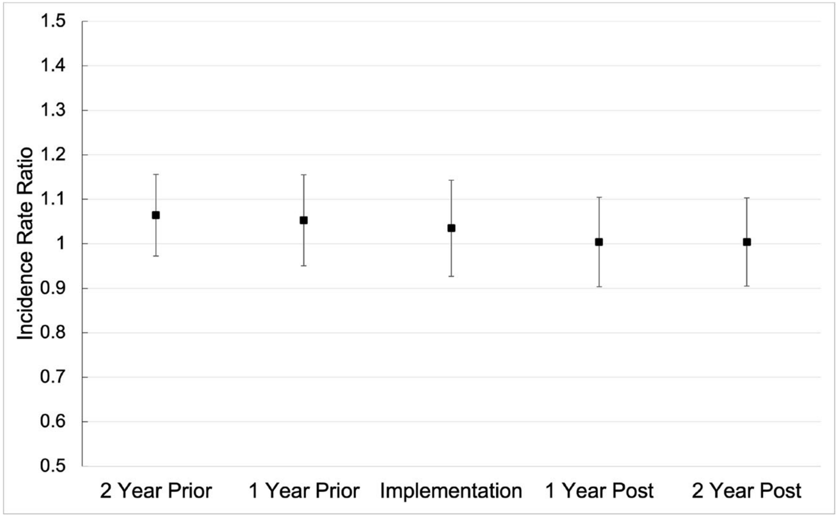

Fig. 3 Lead and lag models for ShotSpotter implementation and firearm homicides among large metropolitan counties, 1999–2016

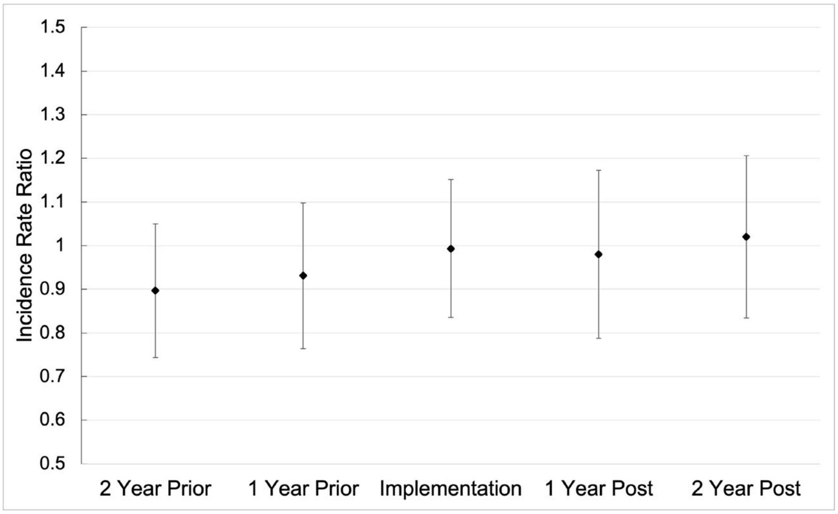

Fig. 4 Lead and lag models for ShotSpotter implementation and murder arrests among large metropolitan counties, 1999–2016

Our insignificant findings within the 1- and 2-year lag models suggest that 1- and 2 years after implementation, ShotSpotter technology did not have a significant association with county-level firearm homicides, murder arrests, and weapons arrests.

Previous research examining the impact of ShotSpotter on outcomes have been mixed; these evaluations have demonstrated an increased awareness of shooting incidents [17] and thus reduced response times [13]; however these findings do not translate into improved outcomes. Yet, ShotSpotter technology is billed as a means to reduce crime and increase arrests through reducing law enforcement response times to shootings. Theoretically, if time from firearm discharge to police arrival is shortened significantly, the ability for law enforcement to intervene and collect evidence is increased, and so too their ability to make arrests.

Other aspects of our findings align with current research which indicate that PTP laws impact state firearm homicides [21, 22, 36] and county-level firearm homicides [18]. Controlling for the presence of ShotSpotter, we found that counties in states with PTP laws had a 15.7% reduction in firearm homicide incidence compared with counties in states without such laws. Counties in states with RTC laws saw an increase in 21.4% in firearm homicide incidence compared with counties in states without such laws. These findings are notable and similar to the associations found by

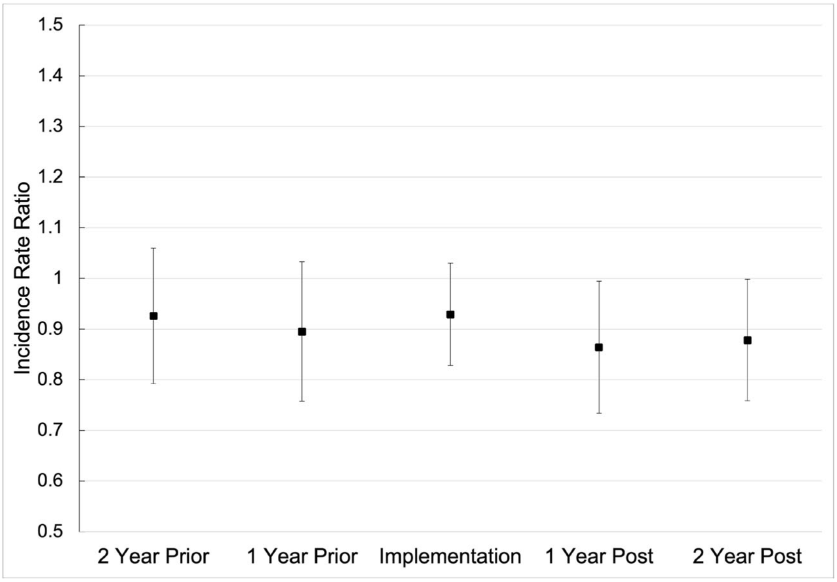

Fig. 5 Lead and lag models for ShotSpotter implementation and weapons arrests among large metropolitan counties, 1999–2016

Crifasi and colleagues [22]. States with PTP laws are thought to have lower criminal gun diversion, or straw purchases [37], as well as lower guns exported across state boarders which were used in crimes and lower homicide rates in general [38]. Increasing handgun purchaser requirements is likely a means to reduce urban firearm violence given previous evidence and evidence presented here. States with RTC laws have a higher proportion of loaded firearm carrying [39] and are associated with higher rates of firearm homicides overall and firearm homicides among workers [21, 22]. Rolling back RTC laws would likely reduce the prevalence of loaded firearm carrying in public spaces, including large urban centers, which may reduce the lethality of interpersonal violence overtime. These policy solutions may impact large metropolitan firearm homicides.

Limitations

The primary limitation of this study is our inability to directly assign outcomes to the exact census tract covered by ShotSpotter. This limitation is applicable to both our dependent and independent variables. ShotSpotter uses proprietary technology and does not disclose the exact census tract coverage; although there have been calls to make this data public in order to scientifically evaluate the technology's impact and effectiveness on reducing firearm violence in urban centers [27]. To our knowledge, there is also a lack of reliable and valid incidence data for nationwide firearm homicides at the census tract level that encompasses the total duration of the study period. Given these two limitations, the ability to examine deaths that occurred in only ShotSpotter covered zones is not possible at this time. Additionally, we used the ShotSpotter website to identify counties with deployed ShotSpotter technology. As a result, our analysis may have missed counties that implemented ShotSpotter, but ultimately discontinued use.

Not properly attributing the rate of firearm deaths and arrests to the exact area covered by ShotSpotter biases our results toward the null hypothesis of no relationship as we are including deaths and arrests that occur outside of the ShotSpotter covered region where we would expect a change in incidence to occur. However, large metropolitan counties where municipalities chose to purchase ShotSpotter likely implement the technology in areas where the largest proportion of urban firearm violence occurs. Therefore, outer lying regions that are included within the large metropolitan county but are not covered by ShotSpotter likely see lower levels of firearm violence incidence comparatively. If both of these assumptions are true across our study population, then ShotSpotter technology should have displayed a significant reduction in the average effect of county-level firearm violence and an increase in murder arrests and weapons arrests, as a large portion of our outcomes would have occurred in the ShotSpotter covered areas. This relationship was not borne out by our analysis.

A major limitation of ShotSpotter and other GDT is its inability to detect gunshots indoors. It is currently unknown what percentage of homicides are committed indoors versus outdoors. However, if ShotSpotter only picks up gunfire outdoors, it is ineffective in assisting law enforcement with a proportion of shooting incidents that occur in people's homes, for example. Likewise, we cannot disaggregate our outcomes to reflect outdoor (ShotSpotter detected) versus indoor (ShotSpotter not detected) firearm violence. Nevertheless, if ShotSpotter was effective, we should see some change in the average firearm outcomes, and we do not. Future technology may include detection means through existing home-based handheld or console-type detection devices not previously configured for this purpose.

The study scope may also be a limitation. The implementation of ShotSpotter, or any GDT, addresses only one part of the investigative process: early notification of a gun discharge to law enforcement. Once notified, law enforcement needs to respond, collect evidence, and investigate before a potential arrest. The extant literature investigates the impact of ShotSpotter on LEAs' knowledge of shootings; EMS response times; and, with this paper, firearm homicides, murder arrests, and weapons arrests. While the literature acknowledges the increased workload and strain of significant increases in gunshot reports that accompany ShotSpotter implementation, little has been done to investigate the impact on the fidelity and timeliness of police operations. One consequence of implementing ShotSpotter without changing staffing numbers or configurations may be the inability of LEAs to take advantage of the decreased reporting time and complete thorough and quick investigations in order to make arrests.

Future research efforts should include census tract data, both in ShotSpotter coverage and crime outcomes, to better our understanding of whether this technology has affected urban violence and arrest rates. This may be possible on a county-by-county basis, working in tandem with local LEAs to understand coverage areas and crime rates. As ShotSpotter operates in the context of LEAs, and within subunits (stations or offices) of those agencies, understanding the impact, or potential impact, of the technology must take into consideration the context in which it operates. Future evaluations must include ShotSpotter fidelity of implementation and the impact of ShotSpotter on fidelity of LEAs investigative and arrest processes and procedures for firearm violence.

Conclusion

This study adds to the relatively new body of literature which suggests a limited effectiveness of ShotSpotter technology on urban firearm violence prevention. Despite minimal evidence-based peer-reviewed research, ShotSpotter technology has been implemented throughout the USA, with more than 100 cities implementing the technology since it was made commercially available in the mid-2000s. Given the proliferation of ShotSpotter technology throughout the USA, there is a need to understand its overall impact as a tool for law enforcement to reduce the incidence and cost of gun violence in American cities.

As noted earlier, the cost of gun violence to the US economy is approximately $229 billion. After an initial setup charge of $10,000 PSM covered, ShotSpotter fees range from $65,000 to $90,000 PSM/year [14]. This implies that cities like New York and Chicago, where ShotSpotter is implemented in 60 mi^2, may spend between $3.9 million and $5.4 million a year on the technology. However, if this investment is not reducing gun-related crime or deaths, nor improving arrest rates of perpetrators, then the expenses associated with implementing and maintaining GDT may be adding to the cost of gun violence rather than reducing it. In fact, there is a lack of evidence to support a return on investment (monetary or otherwise) from implementing this technology. LEAs and the municipalities in which they are located need to consider if this annual budget line item is the most effective approach to reduce urban gun violence.

Our paper adds to the literature that demonstrates the potential for policy to impact homicide rates in a more meaningful way than GDT. Large metropolitan counties in states with PTP laws had significant reductions in firearm homicides. Understanding the relationships between ShotSpotter and firearm homicide rates and related arrests, and policy and firearm homicide and arrest rates, will provide state and municipal leaders, LEAs, and public health officials with the information to make informed decisions about how best to use limited resources in their efforts to reduce violence and death from firearms.

Acknowledgements The Authors have no funding to report.

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