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The Impacts of Large-Scale License Plate Reader Deployment on Criminal Investigations

Christopher S. Koper[1] and Cynthia Lum[1]

Abstract

The use of automated license plate readers (LPRs) has spread rapidly among American police in recent decades. However, research on LPRs has been very limited and focused primarily on small-scale use of LPRs in patrol. This study expands the evidence base on LPRs by evaluating investigative use of a large-scale fixed LPR network in one populous city. Survival analysis methods were used to assess changes in the likelihood and timing of investigative case closures in this city following installation of a fixed network of nearly 100 LPRs. The analysis focused on auto theft, theft of vehicle parts, and robbery investigations, which account for most uses of LPRs by investigators. Case clearances for auto theft and robbery improved after the installation of the LPR network, particularly in places where LPRs were concentrated. However, these changes were not statistically significant in multivariate analyses, and patterns in the data suggest that other factors may have also contributed to higher clearances during the intervention period, particularly for auto theft cases. Results suggest that large-scale LPR deployment may have the potential to improve investigative outcomes for some serious crimes—particularly with more consistent use and better placement for investigations—but further assessment is needed. More generally, additional research is needed to determine the best uses of LPRs, the

[1]Department of Criminology, Law and Society, George Mason University, Fairfax, VA, USA

Corresponding Author:
Christopher S. Koper, Department of Criminology, Law and Society, George Mason University, 4400 University Drive, MS 6D12, Fairfax, VA 22030, USA.
Email: ckoper2@gmu.edu

optimal scales and methods of LPR deployment, and the full range of costs and benefits associated with LPR use.

Keywords
license plate readers, police technology, criminal investigations, robbery, auto theft, survival analysis

Introduction

In recent years, police have increasingly sought to improve their efficiency and effectiveness, especially in the investigation and clearance of crime, through the use of new technologies. One relatively new surveillance and information-gathering technology that has spread rapidly in American policing in the last 10 years is license plate recognition technology (Lum et al., 2018). Automated license plate readers (referred to hereafter as LPRs) are high-speed camera and information systems that read vehicle license plates in real-time (using optical character-recognition technology), check them instantaneously against databases with license plates linked to vehicles and persons of interest (e.g., stolen vehicles, stolen license plates, and vehicles linked to wanted persons), and give automatic alerts when matches are made. LPRs thus enhance the ability of police to detect stolen vehicles and wanted persons in real-time. LPRs also record and store the date, time, and location of scanned plates, which increases their value for a variety of additional investigative purposes. Police have the option of installing LPRs in police vehicles for mobile surveillance or setting them at fixed, strategic positions.

Given these capabilities, LPRs would seem to have considerable potential to enhance patrol, investigative, and other security operations. Indeed, LPRs are a very popular police technology and have been acquired by roughly two thirds of large police agencies (100+ officers) in the United States (Lum et al., 2018). However, research on the uses and impacts of LPRs is very limited. Prior studies of LPRs, conducted in the United States and abroad, have focused largely on demonstrating the accuracy and efficiency of the devices in scanning license plates and their utility for increasing arrests, recoveries of stolen vehicles, and seizures of other contraband (e.g., Cohen, Plecas, & McCormick, 2007; Maryland State Highway Administration, 2005, pp. 58–83; Ohio State Highway Patrol, 2005; Ozer, 2010; PA Consulting Group, n.d., 2004; Potts, 2018; Taylor, Koper, & Woods, 2011, 2012). In contrast, there is scant evidence on whether LPR use actually improves investigative clearances or reduces crime (Lum et al., 2018; Lum & Koper, 2017, pp. 120–124).

In practice, crime prevention and investigative outcomes from the use of LPRs likely depend on several factors, including the volume of LPR deployment, the manner in which LPRs are deployed (mobile vs. fixed), the types of data accessed by LPR systems, how officers use LPRs in the field, how LPR data are saved and used for investigations, and the public's reaction to (and influence upon) LPR use. Evidence on these issues is extremely limited, however, as rigorous outcome evaluations to date have focused on small-scale use of LPRs, primarily in patrol (Koper, Taylor, & Woods, 2013; Lum, Hibdon, Cave, Koper, & Merola, 2011; Ozer, 2010; Potts, 2018; Wheeler & Philips, 2018). Accordingly, given the amount of resources spent on LPRs, there is much need to build a stronger and broader evidence base on LPR applications to inform police decisions about LPR adoption and uses.

To that end, this study examines the potential of large-scale LPR deployment to improve criminal investigations. It is based on the experience of the Charlotte-Mecklenburg, North Carolina Police Department (hereafter, CMPD), which has nearly 100 LPRs deployed at dozens of fixed locations in its jurisdiction. The study describes how CMPD investigators use LPRs for various types of investigations and tests whether the installation of the LPR network has improved the agency's clearance rates for multiple types of crime.

The CMPD study adds to LPR evaluation research in multiple ways. For one, it provides unique new evidence on the efficacy of LPR use for criminal investigations. Police agencies are increasingly using LPRs to investigate a wide variety of crimes beyond auto and license plate theft. Uses of LPRs now extend to investigations of person and property crimes, missing and vulnerable persons, gangs, vice, counterterrorism, and traffic and vehicle violations (Lum et al., 2018). Yet, despite this trend, there has been little study of these investigative applications of LPRs.[1]

The CMPD study is also notable in that it highlights *fixed* LPR deployment. Although police most commonly mount LPRs on moving patrol cars, they deploy about one-quarter of their units at fixed locations (Lum et al., 2018). The relative advantages and disadvantages of fixed versus mobile deployment have received little attention, as studies of LPRs to date have largely focused on patrol use (for an exception, see Ohio State Highway Patrol, 2005). However, fixed deployment may have advantages for many investigative applications because it provides constant surveillance and a permanent record of vehicles using selected roadways. Placed at strategic roads and intersections (e.g., roads with high volume traffic in high crime areas), fixed LPRs may increase the chances of detecting suspect vehicles, including those traveling to or from crime scenes. This can prove valuable for real-time apprehension, follow-up investigations, and other types of targeted investigations.

A final point is that the CMPD study attempts to quantify the effects and value of large-scale LPR deployment. Currently, most agencies using LPRs possess only a small number. Even among large agencies that own LPRs, three-quarters own fewer than 8 units, 90% own less than 15, and only 5% own more than 25 (Lum et al., 2018). Nonetheless, the numbers of LPRs owned by agencies has been growing, and many agencies plan to expand their LPR acquisition (Lum et al., 2018). In principle, expanding LPR deployment should increase its potential impacts for patrol and investigations, but further evaluation is needed to guide agencies on the value and cost efficiency of making larger investments in this technology.[2]

Study Site and Context

Charlotte-Mecklenburg is a consolidated city-county jurisdiction with a population of roughly 1 million people covering about 546 square miles.[3] The core of the jurisdiction is the city of Charlotte, which has nearly 800,000 residents. The CMPD, an agency with about 2,000 sworn officers and 2,400 total employees, is responsible for policing most of the jurisdiction. In 2016, the CMPD investigated approximately 6,600 violent crimes and 36,700 property crimes based on UCR Part 1 offenses.[4]

LPR History and Capabilities

At the time of this study, the CMPD had 95 LPRs located at 44 fixed positions throughout the city, each of which typically had multiple LPR units covering different sides, directions, and portions of the location's roads and intersections. The agency had 14 additional units that were mostly mounted on mobile trailers or patrol vehicles. The CMPD acquired most of these LPRs in 2012 with federal funding to provide additional security for the Democratic National Convention (DNC), which was held in Charlotte-Mecklenburg in September of that year. Because the LPR network was initially installed to meet security concerns for this convention, the LPRs were largely concentrated on key roadways in the city's downtown and in other central areas. At the time of this study, the fixed LPRs were located in nine of the agency's 14 geographic divisions. In those divisions with LPRs, the number of LPR locations ranged as follows: one location (three divisions), three locations (one division), four locations (one division), six locations (two divisions), eight locations (one division), and 14 locations (one division).

The data feeding the CMPD's LPR system include multijurisdictional data on stolen vehicles, stolen license tags, and vehicles linked to persons with open warrants, AMBER alerts, U.S. Department of Homeland Security watch lists, and other vehicles of interest (i.e., ad hoc, "be-on-the-lookout" entries for persons and vehicles of interest).[5] License plate scans and images are saved in the CMPD's data systems for 6 months, unless longer retention is required for a specific investigation. These historical scans can be used for investigations in a number of ways described later.

In addition, the LPR scans are fed instantaneously to the CMPD's real-time crime center (RTCC), which provides investigative personnel in this center with the ability to direct apprehension efforts in the field in real-time when warranted.[6] (Patrol officers also have the ability to monitor LPR reads from their mobile computers, but they largely rely on RTCC officers to monitor the LPRs and direct responses.) When RTCC investigators receive a hit on a stolen vehicle, for example, they send this information out to patrol. RTCC staff also monitor priority calls (primarily violent crimes, such as robberies or assaults) and disseminate information to patrol officers as quickly as possible following a crime's commission (usually within the first 20 minutes of its occurrence). Often, they can use LPRs and other video cameras (see later) to track fleeing suspects and provide information to assist in pursuits. When RTCC investigators obtain a full or partial license plate number for a priority incident, they enter this information manually into the LPR system to immediately track any new or recent LPR hits that might help to locate the wanted vehicle.

A final point about the CMPD's technological capabilities is that the agency also has access to an extensive network of over 500 video cameras owned by the CMPD, the state transportation authority, and local businesses. These cameras are generally concentrated in the same areas as are the agency's LPRs. This enables CMPD investigators to use LPRs and other surveillance cameras in tandem to identify and locate suspect vehicles.

Uses of LPRs

Although the LPR network was not initially adopted for investigative purposes, leaders and investigators in the agency began to think after the DNC about how they could leverage this capability for purposes other than monitoring vehicles at high-risk locations and investigating stolen vehicles and license plates. By the time of this study, the agency was using its LPRs on a regular basis for a wide variety of person, property, and specialized investigations. As a first step to this evaluation, these uses of LPRs were studied in multiple ways. Details of this assessment are available elsewhere (Koper et al., 2018; Willis, Koper, & Lum, 2018), but key results are described here.

Interviews and focus groups conducted with a variety of CMPD staff (primarily detectives, RTCC staff, crime analysts, and commanders) revealed that they viewed LPRs as valuable investigative tools. Common investigative uses of LPRs—besides searching for stolen vehicles and license plates—included rapid response (i.e., real-time pursuit of suspects), developing leads for follow-up investigations (e.g., mining the data from LPRs located near crime scenes), tracking movements of suspects, identifying suspects' accomplices (i.e., looking for vehicles that often travel together), and corroborating statements from suspects and victims (e.g., using LPR scans to verify a suspect's alibi about his or her whereabouts at a particular time). Detective interviews and examination of selected incident narratives (see later) highlighted numerous cases in which LPR hits on full or partial license plate information led directly to the apprehension of suspects in stolen or wanted vehicles. Investigators also described instances in which they cross-referenced LPR records from multiple locations to identify vehicles that were in the vicinity of multiple crime scenes. LPR vehicle images were also valuable in identifying suspects because they sometimes helped investigators to determine the license plates of vehicles that were near crime scenes and matched witness descriptions. In other instances, LPRs were not critical to solving cases but helped detectives to strengthen evidence or resolve cases more efficiently. Examples included cases in which investigators identified or apprehended suspects through other means but used LPRs to locate suspects more quickly or to verify information about a vehicle (e.g., its match to a witness description) or study its previous movements.

However, while investigators reported that LPR use was commonplace and encouraged by command staff, the agency did not have formal policies or mechanisms requiring LPR use or systems for recording and tracking it. LPR use was still spreading in the agency and appeared somewhat dependent on the discretion and initiative of individual supervisors and detectives, as well as their familiarity with the technology (the agency had made basic LPR training available, but knowledge of its more advanced applications was spreading more informally). Investigators noted that they typically mentioned any use of LPRs in the narrative portions of their case reports, but the agency's report forms did not have an easily identifiable indicator for LPR use.

Therefore, in order to quantify the nature and level of the agency's LPR uses, the research team analyzed files on nearly 117,000 incidents investigated by the CMPD from 2011 through early 2015. This analysis was based on all auto-related offenses, UCR Part 1 offenses, and other selected incidents that, given our interviews, the research team thought might be more likely to involve LPR use (e.g., felony traffic offenses and missing person cases). (Note that case reports dating back to 2011 were analyzed because the CMPD had a small number of mobile LPRs prior to the installation of the LPR network. Furthermore, this facilitated a trend analysis of LPR use that was used to design the outcome evaluation described later.) All main and supplemental reports associated with these cases were obtained from the CMPD in electronic form and analyzed for any mention of LPRs.[7] This revealed 4,047 cases in which investigators referred to LPRs in the case narratives (nearly all of these uses occurred from 2013 through 2015 after the installation of the LPR network). Auto theft and theft of auto parts cases each accounted for about a quarter of LPR uses, and robbery cases accounted for 17%. Thefts from motor vehicles, aggravated assaults, and burglaries each accounted for roughly 6% to 8% of LPR uses, while a variety of other incident types (e.g., homicides, missing persons, and thefts) each accounted for less than 5%.

The prevalence of LPR use was 5% to 7% for the analyzed crime types overall during the post-implementation period. However, investigators reported using LPRs in more than a fifth of auto theft and robbery cases and nearly half of homicide and theft of vehicle parts investigations (which include thefts of vehicle license plates).[8] As a caveat, interviews with detectives suggested that the recording of LPR use in case narratives was somewhat variable and seemed more likely when the technology produced useful results. Consequently, these figures may understate LPR use to some degree. Nevertheless, they suggest a substantial level of LPR use for investigating auto-related crimes and certain types of violent offenses.

Finally, to provide some sense of how LPR use affects case outcomes, the research team analyzed the narratives of 200 randomly selected incident reports with reference to LPR use for any offense type. This revealed that LPRs helped investigators to resolve a case in roughly one of five investigations (19%) in which they were used. Findings were consistent with insights from the detective interviews in showing that the LPR hits were not always the sole or critical factor in resolving these cases, nor did all of these cases warrant or result in arrests. Nonetheless, it appeared that LPRs had contributed in some manner to the likelihood or speed of resolving these incidents.

Data and Methods

To determine whether the use of LPRs has measurably improved investigative clearance rates in Charlotte-Mecklenburg, a series of analyses were conducted to test whether there were significant changes in the likelihood and timing of case clearances after the installation of the LPR network. These analyses focused on the crimes of auto theft, theft of vehicle parts, and robbery, which constitute the three offense types for which investigators most frequently use LPRs.[9] During the post-LPR period described later, investigators used LPRs for 45% of theft of vehicle parts cases, 22% of auto theft cases, and 21% of robbery cases. However, this discussion highlights only auto theft and robbery cases because there was no evidence of improvements in theft of vehicle parts investigations (which have very low clearance rates) in any analyses conducted.

As a starting point, the preliminary examination of randomly sampled LPR incidents (discussed earlier) suggested that LPRs helped investigators in some manner to resolve roughly 5% of the auto theft cases and 16% of the robbery cases in which they were used (e.g., through identifying a suspect or helping investigators to resolve a case more quickly irrespective of whether an arrest was made). Given that investigators used LPRs for 21% to 22% of these cases, this implies, as a ballpark figure, that LPRs may have contributed to the likelihood or speed of closure in roughly 1% of auto theft cases and 3% to 4% of robbery cases across the city after the LPR network was established.[10]

To examine LPRs' impacts more formally, case clearances for these offenses were compared for samples of cases that occurred before and after the installation of the LPR network (referred to as the pre-LPR and post-LPR samples, respectively). The selected pre-LPR cases include those that occurred from

January 2011 through June 2012. The post-LPR sample consists of cases that occurred from July 2013 through September 2014. The July 2013 start date for the post-LPR cases was after the full phase-in of the LPR network and RTCC, and it was selected based on a monthly analysis of LPR usage as identified through the search of incident reports described earlier. The September 2014 cutoff date for the post-LPR period was selected so that all pre-LPR and post-LPR cases could be followed for 6 months following the offense (the data received from the CMPD for this analysis extended through March 2015). The combined pre-LPR and post-LPR samples totaled 5,396 for auto theft cases and 4,410 for robbery cases.

Each case in the pre-LPR and post-LPR sample was followed for 26 weeks (approximately 6 months) to determine if and when the case was closed during that period.[11] Case closures were defined as closures through arrest, which accounted for the vast majority of closures, or closures through other exceptional means (primarily cases in which the suspect was identified but the victim declined to prosecute).[12]

To test for changes in the likelihood and timing of case clearances during the post-LPR period, survival analysis techniques (e.g., see Allison, 1995) were used to analyze the time from each crime's occurrence until its clearance by police or the end of the 26-week follow-up period, whichever came first. Cases not solved after 26 weeks were censored, meaning that we know only that the case was not cleared during the time that elapsed between its commission and the end of the study period. In this application, survival analysis techniques help to illuminate whether investigations were more likely to be cleared or whether they were cleared more quickly (potentially saving resources) during the post-intervention period while controlling for other case-level characteristics that may affect closure. Survival analysis methods have been used in prior studies of homicide investigations to determine the impact of various factors on how long homicide cases take to resolve (see Regoeczi, Jarvis, & Riedel, 2008; Roberts, 2007; Roberts & Lyons, 2009).

The life table method was first used to examine the likelihood that cases were closed within selected follow-up periods (adjusted for the time that each case was open) and to test for differences in the distribution of clearance rates across the pre and post-LPR periods.[13] For each crime type, life tables with 1 week intervals were estimated for all cases and separately for cases that were not solved on the day the offense occurred. The latter set of analyses was conducted to determine whether LPRs have had different effects on cases requiring greater investigative follow-up effort.[14] If there were indications of improvement in clearances over time, the analyses were also run without LPR-related cases (which were identified based on the descriptive analysis discussed previously). This step was taken to give some further indication as to whether improvements in clearances were due specifically to LPR cases or, conversely, whether they were due in any measure to more general trends in the agency. However, these analyses should be interpreted cautiously. Their results could be misleading if investigators are more likely to use LPRs (or to report LPR use) for cases that are generally easier or harder than other cases.[15] They could also be affected by errors in the measurement of LPR use caused by failures to note LPR use in case narratives or references to LPRs that did not involve actual use.[16]

If the life table analyses yielded evidence of improvements in clearances during the post-LPR period that were at least moderately statistically significant (i.e., with $p < .10$), the results were tested further with multivariate Cox proportional hazards (CPH) models that assessed changes in clearances over time while controlling for a limited number of case characteristics that were readily available from the CMPD's records management system. The CPH models estimate changes in a case's hazard rate, which here represents the risk that a clearance occurred at a given point in time, conditional on clearance not having occurred before that point.[17] Data that could be readily obtained for each case from the CMPD's records management system included the month and geographic division of occurrence; type of place where the offense occurred (residential, retail, open area, public, or commercial); and indicators for gang, juvenile, and domestic violence involvement. Preliminary analysis revealed these variables had statistically significant associations in many instances with case clearance and LPR use.

Both citywide and localized analyses were conducted. Although the CMPD has divisions and patrol beats without LPRs, this study does not have any true comparison areas. Because suspects in vehicles can drive anywhere in the city, investigators often use LPRs for cases that occur in places with few or no LPRs.[18] Nonetheless, a series of localized analyses were conducted to determine whether there were greater changes in clearances in patrol beats with LPRs or in divisions with higher concentrations of LPRs. These analyses are based on the hypothesis that investigators might be more likely to obtain useful leads through LPR use when crimes happen in the vicinity of LPRs. For the beat-level analyses, patrol beats with one or more LPR units were contrasted with beats having zero LPRs via life table analyses (in beats with LPRs, the number of LPR locations generally ranged from one to four with a maximum of eight). For the division-level analyses, the four geographic divisions having six or more LPR locations were categorized as divisions with high LPR concentrations and contrasted through life table analyses with low LPR divisions having fewer or zero LPRs (LPR locations for these divisions ranged from zero to four). Division-level crime counts and clearance rates are provided by crime type and time period in Online Appendix Table 1.

Multivariate CPH models estimated for the localized analyses took two forms. In one set of models, the likelihood of clearance was analyzed through a difference-in-differences model that included an LPR area indicator, which estimates differences between the LPR areas (i.e., patrol beats with LPRs or the divisions with high LPR concentrations) and other areas at the baseline, pre-LPR period; a post-LPR indicator, which estimates changes in clearance during the post-LPR period that were common across all areas (i.e., any general improvement in clearance that was independent of LPR use); an interaction term between the LPR area and post-LPR period indicators that estimates any difference in the post-LPR change between the LPR areas and other areas; indicators for the month of the year when the offense occurred (to capture seasonal effects); and indicators for the other measured case characteristics (i.e., the type of location where the offense occurred and flags for involvement of gang members, juveniles, or domestic violence). In the second set of models, the likelihood of clearance was modeled as a function of a post-LPR indicator for the general trend in clearance across all areas; an LPR count variable for the number of LPR locations in the patrol beat or division where the offense occurred during the post-LPR period (this variable was coded as zero for all areas during the pre-LPR period); a set of indicators for the patrol beat or division where the offense occurred that control for differences across areas that were constant over time (i.e., fixed effects for areas); indicators for the month of the year when the offense occurred; and indicators for the other measured case characteristics. Key features of each set of models (i.e., the difference-in-differences models and the location count models) are also summarized in Online Appendix Table 2.

Results

For brevity, the discussion and tables highlight the division-level analyses. Citywide and beat level analyses are briefly summarized.[19]

Auto Theft Results

For the city overall, there were no indications of significant improvements in clearances for auto theft cases during the post-LPR period. However, the clearance rate did improve in divisions with high LPR concentrations ($p \leq .05$). As shown in Table 1, improvements were evident in the 1-week clearance rate and grew over time. For the full 26-week follow-up period, the clearance rate improved from 10.2% in the pre-LPR period to 13.7% in the post-LPR period, an absolute increase of 3.5 percentage points and a relative improvement of 34%. In contrast, the improvement in long-term clearance rates was smaller and not statistically significant for the divisions that had lower LPR concentrations or no LPRs at all (Table 2). For example, the 26-week clearance rate in these divisions increased less than 1 percentage point, from 11.4% in the pre-LPR period to 12.0% in the post-LPR period. The divisions with few or zero LPRs tended to have similar but lower clearance rates than did the divisions with high LPR concentrations at all follow-up times during the post-LPR period.

Table 1. Pre–Post Changes in Auto Theft Clearances in Divisions With High LPR Concentrations: Clearance Rates for Selected Follow-Up Periods (All Cases).

Follow-up time	Pre-LPR clearance (%)	Post-LPR clearance (%)	Percentage point change
1 Week	4.4	4.9	+0.5
2 Weeks	6.4	7.3	+0.9
3 Weeks	6.9	8.7	+1.8
4 Weeks	7.8	9.1	+1.3
8 Weeks	9.2	11.3	+2.1
13 Weeks (approximately 90 days)	9.9	13.0	+3.1
26 Weeks (approximately 180 days)	10.2	13.7	+3.5

Note. Life table estimates ($n = 939$ pre-LPR, 629 post-LPR). The estimates of clearance are based on 1 minus the likelihood that the case would "survive" without clearance to the selected week, with the difference then converted to a percentage. Differences statistically significant at $p \leq .05$ with log-rank and Wilcoxon tests. LPR = license plate reader.

Table 2. Pre–Post Changes in Auto Theft Clearances in Divisions With No LPRs or Low LPR Concentrations: Clearance Rates for Selected Follow-Up Periods (All Cases).

Follow-up time	Pre-LPR clearance (%)	Post-LPR clearance (%)	Percentage point change
1 Week	3.3	4.6	+1.3
2 Weeks	5.3	6.8	+1.5
3 Weeks	6.8	8.4	+1.6
4 Weeks	7.8	8.8	+1.0
8 Weeks	9.7	10.4	+0.7
13 Weeks (approximately 90 days)	10.3	11.1	+0.8
26 Weeks (approximately 180 days)	11.4	12.0	+0.6

Note. Life table estimates ($n = 2,283$ pre-LPR, 1,545 post-LPR). The estimates of clearance are based on 1 minus the likelihood that the case would "survive" without clearance to the selected week, with the difference then converted to a percentage. Differences not statistically significant ($p > .10$) with log-rank or Wilcoxon tests. LPR = license plate reader.

For the divisions with high LPR concentrations, additional analyses (not shown) indicated that the clearance rate also improved significantly for cases not solved the same day. When LPR-related cases were removed from the sample in these areas, results were similar but somewhat diminished. The 26-week clearance rate for auto thefts improved from 9.8% in the pre-LPR period to 12.9% in the post-LPR period, and the overall change in clearances across the two periods was moderately significant ($p = .07$–$.08$). This suggests that other factors (such as the RTCC, the availability of other

Table 3. Changes in the Likelihood of Auto Theft Case Closure During the Post-LPR Period Across High and Low LPR Divisions (Difference-in-Differences Hazard Model Estimates With All Cases).

Model indicators	Hazard ratios [95% confidence intervals]
Post-LPR period	1.19 [0.97, 1.45]*
Division with high LPR concentration	0.96 [0.75, 1.22]
Interaction of post-LPR period and division with high LPR concentration	1.13 [0.79, 1.61]

Note. $N = 5{,}396$. Coefficients adjusted for type of location where offense occurred; month of occurrence; and involvement of gang members, juveniles, and domestic violence. LPR = license plate reader.
$^{*}p < .10$.

surveillance cameras, and other changes in police practices) likely contributed to the improvement in clearances in these divisions, though LPRs may have still been relevant.

The division-level effects of LPRs were further explored with multivariate CPH models estimated with the full sample of cases across time periods and divisions. Results from the first model are presented in Table 3, where three key model terms are highlighted: the general post-LPR term, the general term for divisions with high LPR concentrations, and the high LPR division by post-LPR period interaction term. The effect of each variable is presented as a hazard ratio, which shows the indicator's multiplicative impact on the hazard rate of event occurrence (i.e., the likelihood of clearance). Ninety-five percent confidence intervals are also presented for each estimated hazard ratio.

Across the city, the likelihood of clearance increased by a factor of 1.19 (i.e., 19%) for cases that occurred during the post-LPR period, though this change was only moderately significant ($p = .09$). The high LPR division indicator shows that clearance differences between the high and low LPR divisions were negligible during the pre-LPR period. Finally, the interaction term indicates that the improvement in clearance rates during the post-LPR period was 13% higher in the divisions with higher LPR concentrations. However, this difference was not statistically significant.[20] Furthermore, this coefficient was not diminished when an LPR use indicator was added to the model to control for specific cases in which LPRs were used (not shown). This finding also suggests that other factors may have been driving the higher clearances in areas with high LPR concentrations.

Key results from a CPH model testing the effects of LPR location counts are presented in Table 4. This model again shows that there was a moderately significant improvement in clearances across all divisions during the post-LPR period. However, the LPR count indicator shows only a negligible relationship between clearances and the number of LPRs in a division. The likelihood of

Table 4. Association of Auto Theft Case Closure With the Post-LPR Period and the Number of LPR Locations in a Division (Hazard Model Estimates With All Cases).

Model indicators	Hazard ratios [95% confidence intervals]
Post-LPR period	1.22 [0.99, 1.50]*
Number of LPR locations in the division	1.002 [0.96, 1.04]

Note. $N = 5{,}396$. Coefficients adjusted for type of location where offense occurred; month of occurrence; division where offense occurred; and involvement of gang members, juveniles, and domestic violence. LPR = license plate reader.
$^{*}p < .10$.

clearance increased by less than 1% with each additional LPR location, and this association was not statistically significant.

Variations of the two CPH models were also estimated after excluding cases that were solved the same day (not shown). These models yielded inferences consistent with those discussed earlier.

Results at the patrol beat level were similar to those at the division level. Beats with LPRs had improvements in their clearances relative to beats without LPRs, but multivariate models failed to show significant LPR effects, and patterns in the data suggested that other factors beyond LPR use were contributing to the improvements in the LPR beats.

Robbery Results

At the city level, there was no change in robbery clearances overall, but there was a moderately significant improvement ($p = .06$–$.09$) for cases that were not solved the same day. At 26 weeks, the clearance rate for these cases improved from 30.0% in the pre-LPR period to 32.1% in the post-LPR period (a relative improvement of 7%). This improvement was linked to LPR-related cases; when they were removed from the sample, the pre–post change was smaller and not statistically significant ($p > .10$). However, the post-LPR change was not statistically significant in a multivariate CPH model that controlled for the type of location where the offense occurred; the month of occurrence; the division where the offense occurred; and the involvement of gang members, juveniles, and domestic violence.

Patterns were similar at the division level. In the divisions with high LPR concentrations, there was no change in the overall clearance rate, but there was a moderately significant improvement ($p < .10$) for cases not solved on the day of occurrence (Table 5). Up through the first 4 weeks of follow-up, post-LPR clearance rates were roughly four to five percentage points higher (in relative terms, these changes represented improvements of 23% to 62%). By the end of the 26-week follow-up period, this difference was about 3 percentage points

Table 5. Pre–Post Changes in Robbery Clearances in Divisions With High LPR Concentrations: Clearance Rates for Selected Follow-Up Periods (Cases Not Cleared the Day of Occurrence).

Follow-up time	Pre-LPR clearance (%)	Post-LPR clearance (%)	Percentage point change
1 Wek	7.7	12.5	+4.8
2 Weeks	13.1	18.6	+5.5
3 Weeks	18.2	23.0	+4.8
4 Weeks	21.4	26.3	+4.9
8 Weeks	25.6	29.5	+3.9
13 Weeks (approximately 90 days)	27.6	31.0	+3.4
26 Weeks (approximately 180 days)	29.4	32.5	+3.1

Note. Life table estimates ($n = 771$ pre-LPR, 601 post-LPR). The estimates of clearance are based on 1 minus the likelihood that the case would "survive" without clearance to the selected week, with the difference then converted to a percentage. Differences moderately significant ($p = .07$) with the Wilcoxon test. LPR = license plate reader.

(a relative improvement of 10%–11%). When LPR-related cases were removed from the sample, the improvements in clearance rates in these divisions became smaller and not statistically significant ($p > .10$). Clearance rates for cases not cleared the same day also improved in divisions with zero or fewer LPRs, but the changes were not as large nor statistically significant (Table 6). Clearance rates for these cases were very similar in both groups of divisions during the post-LPR period.

In multivariate CPH models, the overall change in clearances across divisions was not statistically significant (Tables 7 and 8). Moreover, there were no clear indications of improvements linked to LPR use. Clearances were about 6% higher during the post-LPR period in divisions with high LPR concentrations (as indicated by the post-LPR and division interaction term), but this difference was not statistically significant (Table 7). Nor was there a significant association between clearances and the number of LPR locations in a division (Table 8).

Finally, LPRs did not appear to have more localized effects on robbery investigations as measured at the patrol beat level. Beats with LPRs showed some improvement in robbery clearances during the post-intervention period, but the changes were not statistically significant ($p > .10$). This pattern was found for all cases and for cases not solved on the day of occurrence.

Discussion

This study has examined the potential of LPRs to enhance investigations of serious crimes based on the experience of Charlotte-Mecklenburg, a city with

Table 6. Pre–Post Changes in Robbery Clearances in Divisions With No LPRs or Low LPR Concentrations: Clearance Rates for Selected Follow-Up Periods (Cases Not Cleared the Day of Occurrence).

Follow-up time	Pre-LPR clearance (%)	Post-LPR clearance (%)	Percentage point change
1 Week	10.9	11.3	+0.4
2 Weeks	17.2	18.6	+1.4
3 Weeks	21.1	23.0	+1.9
4 Weeks	23.6	25.5	+1.9
8 Weeks	28.0	29.4	+1.4
13 Weeks (approximately 90 days)	29.4	30.7	+1.3
26 Weeks (approximately 180 days)	30.3	32.0	+1.7

Note. Life table estimates ($n = 1{,}659$ pre-LPR, 1,379 post-LPR). The estimates of clearance are based on 1 minus the likelihood that the case would "survive" without clearance to the selected week, with the difference then converted to a percentage. Differences were not statistically significant ($p > .10$) with log-rank or Wilcoxon tests. LPR = license plate reader.

Table 7. Changes in the Likelihood of Robbery Case Closure During the Post-LPR Period Across High and Low LPR Divisions (Difference-in-Differences Hazard Model Estimates for Cases Not Cleared the Day of Occurrence).

Model indicators	Hazard ratios [95% confidence intervals]
Post-LPR period	1.05 [0.92, 1.19]
Division with high LPR concentration	0.98 [0.83, 1.14]
Interaction of post-LPR period and division with high LPR concentration	1.06 [0.84, 1.33]

Note. $N = 4{,}410$. Coefficients adjusted for type of location where offense occurred; month of occurrence; and involvement of gang members, juveniles, and domestic violence. Displayed coefficients were not statistically significant. LPR = license plate reader.

Table 8. Association of Robbery Case Closure With the Post-LPR Period and the Number of LPR Locations in a Division (Hazard Model Estimates for Cases Not Cleared the Day of Occurrence).

Model Indicators	Hazard ratios [95% confidence intervals]
Post-LPR period	1.01 [0.88, 1.17]
Number of LPR locations in the division	1.02 [0.99, 1.05]

Note. $N = 4{,}410$. Coefficients adjusted for type of location where offense occurred; month of occurrence; geographic division where offense occurred; and involvement of gang members, juveniles, and domestic violence. Displayed coefficients were not statistically significant. LPR = license plate reader.

a large fixed LPR network. Deployment of LPRs at fixed positions in particular opens several avenues for innovative ways to use LPRs for investigations. This may prove to be a key advantage of fixed relative to mobile LPR deployment, especially for agencies that have large numbers of LPRs.

The results provide tentative but not conclusive evidence that LPR use may have contributed to modest improvements in case closures for auto theft and robbery, two of the crimes for which CMPD investigators are most likely to use LPRs. The likelihood and timing of clearances for these cases improved after the installation of the CMPD's LPR network, particularly in areas where LPRs were concentrated. For auto theft cases, improvements were most apparent for long-term clearances. For robberies, both short-term and long-term clearances improved for cases that required follow-up investigations. However, the most sophisticated tests did not show statistically significant evidence of greater improvements in areas with more LPRs when controlling for case-level characteristics. Other patterns in the data also suggest that factors beyond LPR deployment contributed to improvements in case closures, particularly for auto theft investigations. These factors might include the use of other technologies by the CMPD, other changes in police investigation and management, or even changes in offense patterns that occurred during this time.

Several caveats should be noted in addition to methodological limitations discussed previously. For one, it was not possible to separate the effects of the LPR network from those that may have stemmed from the RTCC and the extensive network of non-LPR surveillance cameras in Charlotte-Mecklenburg. These technologies are compliments to LPRs that investigators often use in tandem with LPRs. The combined use of these technologies may create synergies that amplify their investigative benefits. At the same time, it is plausible that there is some redundancy among the LPRs and other surveillance cameras that may limit the value of LPRs in this context. In other words, perhaps LPRs have more clearly discernible impacts in environments where there were fewer or no non-LPR cameras. These possibilities raise questions about the relative benefits of LPRs, other types of surveillance cameras, and combinations thereof that may warrant examination in future study.

The outcome evaluation results may also understate LPR benefits in some regards. For example, LPRs may have had effects on more specific categories of auto theft and robbery cases than those examined here (e.g., robbery cases involving vehicles), on crime types not examined here, or in smaller geographic locations (e.g., cases within a certain proximity to an LPR). The outcome analysis also does not likely reflect the full benefits of LPRs for building evidence in a case, conducting highly specialized investigations (e.g., long-term surveillance and investigations of known offenders), and security operations. These issues merit attention in future studies.

Perhaps most importantly, the process and outcome evaluation results suggest the benefits of LPRs are likely to be stronger with more systematic use of

LPRs and more strategic placement of the devices for crime prevention. LPR use was only noted in 21% to 22% of auto theft and robbery investigations during the study period. Although LPR use may not have been consistently recorded in case files, this figure is low enough to suggest that training and policies to encourage more systematic use of LPRs by detectives might be beneficial. Development of systems to document LPR use more consistently would also facilitate stronger tracking and evaluation by police managers and researchers. Future studies could then probe more deeply into the circumstances in which investigators are more or less likely to use LPRs, the circumstances and crime types for which LPR use is most likely to be beneficial, and the effects of policies that promote more systematic use of LPRs.

In addition, CMPD's LPR network was not initially designed for optimal crime prevention and investigation purposes. As noted, the initial placement of the LPRs was driven largely by security concerns associated with the DNC. Although some LPRs were moved to other parts of the city following the convention, they were not highly concentrated in the city's most crime-prone areas during the study period. To contrast LPR distribution with that of crime, 77% of the LPR locations were concentrated in four divisions (those with 6 to 14 locations each) that generated only 29% of the city's auto thefts and 31% of its robberies. At present, however, the agency is in the process of moving more of its LPRs into high crime areas. Perhaps future assessments in Charlotte-Mecklenburg, or in other jurisdictions with more strategic large-scale LPR placements, would reveal stronger LPR impacts.

On the other hand, taken at face value, the evaluation results also raise the possibility that even large-scale LPR deployment may have only modest or negligible effects on overall case clearance rates for serious crimes.[21] LPR deployment may thus need to reach very high volumes or density levels in order to have clearly discernible and substantial impacts on investigative outcomes measured in the aggregate. Despite the large-scale investment in LPRs in Charlotte-Mecklenburg, investigators often noted the need for more LPRs to enhance investigations. For many jurisdictions, including large cities, this may be prohibitively expensive to achieve on a widespread basis.[22] Moreover, the cost efficiency of these investments must also be assessed. Reported LPR costs range from $10,000 to $25,000 per unit for mobile units, with fixed unit costs as high as $100,000 depending on where they are placed (Gierlack et al., 2014). Additional long-term operational and maintenance costs must also be considered. With regard to benefits, LPRs may potentially reduce an agency's cost per clearance by increasing clearances and reducing investigator time and cost per case. If these effects are substantial, they could potentially improve the cost effectiveness of criminal investigations over the long term even when weighed against the costs of LPR acquisition and maintenance (e.g., see discussion in Ozer, 2010). However, additional evidence will be needed to demonstrate these savings more conclusively. To answer questions about the cost–benefit ratio of

LPR expenditures, additional assessments would then also be needed to determine whether LPR-related improvements in case clearance rates reduce crime and, if so, to estimate the monetary value of those benefits relative to the costs of LPRs.[23] Any such savings stemming from crime prevention could also be added to other monetary benefits that LPRs might generate (if applicable) with regard to driving and vehicle violations (e.g., increasing revenue from unpaid fines—see Eberline, 2008; Gierlack et al., 2014; PA Consulting Group, 2004). Although the results presented here arguably provide some tentative grounds for optimism about the benefits of fixed and large-scale LPR deployment, further assessments with other jurisdictions will be necessary to determine whether large-scale LPR deployment has benefits that justify its costs across a range of applications for investigations, crime prevention, and reducing driving and vehicle-related violations.

As a final point, this study adds to a limited body of literature examining whether criminal investigations, and clearance rates in particular, have been improved by advances in a variety of technologies including information technologies (e.g., Brown, 2015; Danziger & Kraemer, 1985; Garicano & Heaton, 2010; Hekim, Gul, & Akcam, 2013; Ioimo & Aronson, 2003; Koper, Lum, Willis, Woods, & Hibdon, 2015, pp. 183–190, 210–233; Nunn, 1993; Zaworski, 2004), closed-circuit television (Ashby, 2017; Piza, Caplan, Kennedy, & Gilchrist, 2015); gunshot detection technology (Mazerolle, Watkins, Rogan, & Frank, 1999), and forensics (Dunsmuir, Tran, & Weatherburn, 2008; Peterson, Sommers, Baskin, & Johnson, 2010; Roman et al., 2008). These studies suggest that the impacts of new technologies can be variable, contingent on a variety of technical, contextual, and organizational factors. Making use of some technologies on a large scale can also pose significant challenges with regard to operational requirements, resources, practicality, and return on investment. This study of LPRs adds to the complexity and mixed findings of this broader body of work. The results underscore the need for a strong commitment to evaluation research on LPRs and other technologies that can help police optimize their decisions regarding technology acquisition and uses.

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Notes

1. On a related note, Ozer (2010) reported that deployment of LPR patrols in one U.S. city increased follow-up arrests (and presumably clearance rates) for minor offenses, controlling for case volume. Similarly, based on pilot results with LPRs in 11 sites, researchers in the United Kingdom have projected that nationwide LPR use will substantially reduce the overall gap between recorded offenses and offenses brought to justice in that country (PA Consulting Group, 2004). However, neither study examined investigative uses of LPRs or changes in case clearances in the manner presented here.
2. Studies of widespread LPR use across numerous jurisdictions have been conducted in the United Kingdom, where all police forces in England and Wales have had LPR capability for over a decade (PA Consulting Group, n.d., 2004, 2006). However, these studies have not examined the impacts of LPR volume within a locality or linked LPR volume specifically to changes in clearance rates or crime. Results from other nations may also not generalize well to the United States, where license plates and relevant databases (on crime, driving/vehicle violations, and other subjects of interest) are less standardized and integrated.
3. U.S. Census Bureau figures accessed March 5, 2018 at: https://www.census.gov/quickfacts/fact/table/mecklenburgcountynorthcarolina/PST045216.
4. Federal Bureau of Investigation figures accessed March 5, 2018 at https://ucr.fbi.gov/crime-in-the-u.s/2016/crime-in-the-u.s.-2016/tables/table-6/table-6-state-cuts/north-carolina.xls.
5. These data capabilities are fairly common compared to other agencies using LPRs (see Lum et al., 2018).
6. The RTCC was established during the same time frame as the LPR network.
7. To perform this query, the reports were scanned for a list of LPR terms that were generated from focus group interviews with CMPD officers and analysts. The complete list of LPR terms included: LPRs, plate readers, license plate recognition, LPR, ALPR (automated license plate reader), ANPR (automated number plate reader), road warrior (a term for the agency's mobile LPRs), dash camera/cam, plate camera/cam, car camera/cam, tag reader, VISCE (a term for a vehicle investigation initiative in the agency), LPR trailers/trailer, road reader, and ran/run the tag.
8. The potential benefits of using LPRs for auto theft and theft of license plate investigations are obvious, though results may be limited by delays in the discovery and reporting of vehicle and license plate thefts, quick abandonment of stolen vehicles by auto thieves, and switching of stolen vehicle license plates by experienced thieves (e.g., see Taylor et al., 2012, p. 26). LPRs may also be particularly helpful for robbery investigations in which victims or witnesses can provide license plate information (full or partial) or a description of a getaway vehicle but do not know the perpetrator(s). LPR use was also often prioritized in homicide cases, given their seriousness.

Furthermore, investigators sometimes used mobile LPRs to canvass areas around homicide scenes. For other offense types examined, LPRs were used in less than 10% of cases, and typically less than 5%. Although not a focus of this study, the low levels of LPR use for these other crimes may reflect a combination of factors including less need for LPR use, lack of investigator familiarity and training with LPRs, less explicit reporting of LPR use, and perhaps lower investigative effort applied to some crime types. The utility of increasing LPR use for a wider variety of criminal investigations may warrant attention in future studies.

9. Although investigators use LPRs in a large share of homicide cases, they were not included in this analysis because the relatively small number that occurred during the study period (40 in the pre-LPR period and 38 in the post-LPR period) precluded rigorous analysis.
10. Among auto theft cases in the random sample, 27% resulted in some kind of hit, and 17% of these hits were helpful in resolving the incidents. As noted, investigators were using LPRs in 22% of auto theft cases during the study period. In combination, these figures suggest that LPR use helped to conclude about 1% of the city's auto theft cases (i.e., $0.27 \times 0.17 \times 0.22 = .01$). For robberies, the projected impact of LPR use was somewhat higher. In the random sample, 42% of LPR uses for robbery resulted in a hit, and 38% of these hits helped investigators to identify and/or apprehend suspects. Given that LPRs were used in 21% of robbery investigations, this suggests that LPRs contributed to the resolution of roughly 3.4% of robbery cases (i.e., $0.42 \times 0.38 \times 0.21 = .034$). These projections should be viewed cautiously because the numbers of auto theft and robbery cases in the sample were relatively small. Furthermore, in many of these cases, LPRs likely contributed more to the speed than to the likelihood of suspect apprehension. Nevertheless, these projections provide initial ballpark estimates of LPRs' possible impacts on these types of investigations across the city. They are also helpful in judging results from the quasi-experimental evaluation that follows, which more formally tests the impacts of the LPR network on CMPD's investigative clearance rates. Further results from this component of the CMPD study are presented in Koper et al., 2018.
11. Preliminary analysis across all offense types during the baseline, pre-LPR period revealed that 96% of solved cases were closed within 180 days (roughly 6 months).
12. Exceptional clearances typically refer to situations in which the agency has identified and located the suspect(s) but cannot arrest the suspect(s) due to circumstances outside the agency's control (e.g., death of the suspect or a victim's refusal to cooperate with prosecution). Note that unfounded cases were excluded from the analysis.
13. In the life table method, the analyst groups the event times into intervals of a chosen length—in this application, weeks—and calculates S_t, which is the probability that the case "survived" (i.e., did not experience the event of interest) to the start of interval t. For each interval, the value of S_t is based on the probabilities of events occurring in prior intervals. For example, the probability of surviving to the third interval or beyond would be the product of $(1\text{-}q_1)(1\text{-}q_2)$, where q_1 and q_2 represent the probabilities of events occurring during intervals 1 and 2, respectively. For a given interval, the probability of an event (conditional on survival to the start of the interval) is denoted as $q = d/(n - m/2)$, where d equals the number of events occurring

during the interval, n refers to the sample at risk at the start of the interval (i.e., the number of cases that have not experienced an event or been censored by the start of the interval), and m is the number of cases censored during the interval (Teachman, 1983, p. 270). For further discussion of the life table method, see Allison (1995) and Teachman (1983).

14. Cases cleared on the same day are likely to have involved suspects who were captured at or near the scene or who were readily apprehended based on identification by victims or witnesses.
15. Comparisons of LPR-related and non-LPR-related auto theft cases showed that LPR use was unrelated to the likelihood that cases would be cleared (based on a chi-square test of proportions) or the time to clearance for those cases that were closed (based on t tests for the average time to closure). These patterns suggest that LPR use did not generally improve case outcomes for auto theft; however, they may also suggest that investigators were more likely to use LPRs in cases that were more difficult to solve. For robberies, LPR-related cases were more likely to be solved than other cases (41.5% to 35.8%, with $p \leq .03$ in a chi-square test for the difference in proportions), but LPR use was not related to the speed of clearance for closed cases. These patterns provide some evidence that LPR use improved robbery clearances, but they could be confounded by other case-level factors related to LPR use. Most notably, it seems very likely that detectives use LPRs when offenders use a vehicle in a robbery and the license plate of that vehicle can be determined based on witness testimony or by reviewing LPR or other video images. When suspect license plate information is available, detectives may have a greater likelihood of identifying suspects and solving cases regardless of whether they use LPRs. Nonetheless, LPR use may be important to these cases if it improves the likelihood of identifying the suspect vehicle's license plate to begin with or improves the likelihood of finding a wanted vehicle. These possibilities could not be explicitly examined with available data but should be noted as caveats in the interpretation of results. (Note that the analysis of robbery cases implicitly assumes that the share of robberies involving vehicle use remained constant over time since this could not be measured using case-level data from the records management system.)
16. The former possibility cannot be assessed with available data but seemed likely based on the interviews and focus groups with CMPD staff. However, the examination of randomly sampled LPR cases noted previously suggests that 14% of cases with references to LPRs were false positives (i.e., cases that did not actually involve LPR use).
17. The CPH model is often expressed as: $h_i(t) = \lambda_0(t)\exp(B_1 x_{i1} + \ldots + B_k x_{ik})$, where $h_i(t)$ represents the hazard for subject i at time t, $\lambda_0(t)$ represents a baseline hazard function (which can be regarded as the hazard function for a subject whose covariates all have values of zero), x_{i1} through x_{ik} represent a set of fixed covariates, and B_1 through B_k represent the effects of those covariates (these effects are then exponentiated) (Allison, 1995, pp. 113–114). The model assumes that the ratio of the hazards for any two subjects remains constant over time (i.e., that they remain proportional to one another) but makes no assumption about the distribution, or shape, of the baseline hazard rate. Estimation of the CPH models was done using robust standard errors (Lin & Wei, 1989).

18. For example, the percentage of auto theft cases in which investigators used LPRs ranged from 7% to 32% across the divisions with LPRs during the post-LPR period. At the same time, this range was 6% to 41% in divisions with zero LPRs. Similarly overlapping ranges were also observed for the share of robbery cases involving LPR use. For both auto theft and robbery, there were also overlapping ranges across divisions with and without LPRs in the percentage of cleared cases in which LPR use was indicated (note that LPR use in cleared cases does not necessarily indicate that LPR use helped investigators to solve the case).
19. Full results of those analyses are available in Koper et al. (2018).
20. Results were similar for a model that compared the divisions with high LPR concentrations to those with no LPRs.
21. For further discussion of the potential benefits and challenges of using LPRs to apprehend minor offenders as well as driving or vehicle-related violators, see Cohen et al. (2007), Ozer (2010), and PA Consulting Group (2004).
22. Even with nearly 100 fixed LPRs at 44 locations, the scale of Charlotte–Mecklenburg's LPR deployment is arguably small relative to the size of the jurisdiction (which limits coverage and perhaps makes it easier for offenders to avoid the LPRs if the fixed devices and their locations become widely recognized). Even the divisions with higher LPR concentrations had relatively few LPR locations. Smaller jurisdictions can achieve higher LPR density levels with fewer devices, but the costs may be particularly difficult for such jurisdictions to manage.
23. See Rossi, Lipsey, and Freeman (2004, pp. 331–368) for further discussion about distinctions between cost effectiveness and cost-benefit analyses in program evaluation.

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Author Biographies

Christopher S. Koper is an associate professor in the Department of Criminology, Law and Society at George Mason University and the principal fellow of George Mason's Center for Evidence-Based Crime Policy. Dr. Koper holds a PhD in Criminology and Criminal Justice from the University of Maryland and has worked previously for the Police Executive Research Forum, the University of Pennsylvania, the Urban Institute, the RAND Corporation, the Police Foundation, and other organizations. He specializes in issues related to policing, firearms policy, and program evaluation.

Cynthia Lum is a professor of Criminology, Law and Society at George Mason University and the director of its Center for Evidence-Based Crime Policy. She researches in the areas of policing, technology, evidence-based crime policy, translational criminology, and crime prevention. She holds a PhD in Criminology and Criminal Justice from the University of Maryland and was a former police officer and detective for the Baltimore City Police Department.