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The Impact of Red Light Cameras (Photo-Red Enforcement) on Crashes in Virginia

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16. Abstract

Red light running is a significant public health concern, killing more than 800 people and injuring 200,000 in the United States per year (Retting et al., 1999a; Retting and Kyrychenko, 2002). To reduce red light running in Virginia, six jurisdictions (Alexandria, Arlington, Fairfax City, Fairfax County, Falls Church, Vienna) deployed red light cameras at some point during the 10-year period when they were permitted under Virginia law.

This report documents the safety impacts of those cameras based on 7 years of crash data for the period January 1, 1998, through December 31, 2004. Consistent with the findings of a previous Virginia study (Garber et al., 2005), this study finds that cameras are associated with an increase in rear-end crashes (about 27% or 42% depending on the statistical method used as shown in Tables ES1 and H1) and a decrease in red light running crashes (about 8% or 42% depending on the statistical method used as shown in Tables ES1 and H2). This report also shows that there is significant variation by intersection and by jurisdiction: one jurisdiction (Arlington) suggests that cameras are associated with an increase in all six crash types that were explicitly studied (rear-end, angle, red light running, injury red light running, total injury, and total) whereas two other jurisdictions saw decreases in most of these crash types.

It is therefore not surprising that when the comprehensive crash costs for rear-end and angle crashes are monetized, the cameras are associated with an increase in crash costs in some jurisdictions (e.g., an annual increase of $140,883 in Arlington) and a net reduction in comprehensive crash costs in other jurisdictions (e.g., an annual reduction of $92,367 in Vienna). When these results are aggregated across all six jurisdictions, the cameras are associated with a net increase in comprehensive crash costs. However, when considering only injury crashes, if the three fatal angle crashes that occurred during the after period are removed from the analysis (the only fatalities that occurred during the study out of 1,168 injury crashes), then the cameras were associated with a modest reduction in the comprehensive crash cost for injury crashes only.

These results cannot be used to justify the widespread installation of cameras because they are not universally effective. These results also cannot be used to justify the abolition of cameras, as they have had a positive impact at some intersections and in some jurisdictions. The report recommends, therefore, that the decision to install a red light camera be made on an intersection-by-intersection basis. In addition, it is recommended that a carefully controlled experiment be conducted to examine further the impact of red light programs on safety and to determine how an increase in rear-end crashes can be avoided at specific intersections.

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FINAL REPORT

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The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Virginia Department of Transportation, the Commonwealth Transportation Board, or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

PREFACE

The authors gratefully acknowledge the essential assistance of the people who made this study possible. The steering committee composed of Mr. Larry Caldwell, Mr. Bernard Caton, the Honorable Dorothy Clarke, Ms. Mena Lockwood, Chief Timothy Longo, and the Honorable Glenn Weatherholtz provided insights and review comments that shaped the direction of the study. The report could not have been completed without the extensive efforts of the people who provided data from localities, including Master Police Officer Ryan Arnold, Mr. Johnny Bloomquist, Ms. Melissa Borja, Mr. Adam Briggs, Mr. Bernard Caton, Mr. Chad Charles, Mr. Bert Dunnavant, Ms. Kimberly Eccles, Captain Daniel Ellis, Ms. Ellen Gallagher, Mr. Daniel Gollhardt, Mr. Louis Koutris, Ms. Ling Li, Mr. Vu Nhan, Lt. David Pelto, Captain Bonnie Regan, Mr. Hari Sripathi, Sergeant Paul Story, Sergeant Mark Summerell, Mr. Bruce Taylor, and Mr. John Veneziano. Internal review comments were provided by Dr. Mike Fontaine, Dr. Jim Gillespie, Dr. Young-Jun Kweon, Ms. Cheryl Lynn, and Dr. Amy O'Leary. The authors also acknowledge the staff at the University of Virginia and the Virginia Transportation Research Council who assisted with this study. The data collection was led by Mr. Lewis Woodson, and assistance to him was provided by Mr. Thomas Bane, Mr. Chris Bryant, Mr. Yuan Lu, Ms. Lily Liu, Mr. Lili Luo, Mr. Koundinya Pidaparthi, Ms. Kristen Torrance, Mr. Matthew Webber, and Mr. Jack Wisman. Graphics assistance was provided by Mr. Randy Combs and Mr. Ed Deasy, and editing was provided by Ms. Linda Evans. Inclusion of these names does not guarantee agreement with the contents of this study, however, and the authors alone are responsible for errors.

The study was directed by Mr. Wayne Ferguson of the Virginia Transportation Research Council. Dr. Nicholas Garber and Dr. John Miller were the principal investigators.

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Introduction

Red light running is a substantive problem that has led to numerous crashes and consequent injuries and fatalities. This phenomenon, which occurs when a motorist enters an intersection after the onset of the red signal, caused almost 5,000 crashes, more than 3,600 injuries, and at least 26 deaths in Virginia in 2004 (Virginia Department of Transportation [VDOT], 2006).

Photo-red enforcement programs address the problem of red light running. The technology consists of a camera that photographs the license plates of vehicles that enter an intersection after the signal has turned red. After a process of review and validation, an approved citation, along with the photograph of the violation, is sent to the registered owner of the vehicle.

These programs were studied in the fall of 2004 (Garber and Miller, 2005) in the Northern Virginia jurisdictions of Alexandria, Arlington, Fairfax City, Fairfax County, Falls Church, and Vienna, and the study report answered several questions concerning the programs. The initial analysis focused on the technical, fiscal, and operational feasibility of photo-red enforcement. The crash portion of the analysis focused most heavily on Fairfax County, with limited crash analysis for Fairfax City, Falls Church, and Vienna, and no crash analysis for Alexandria and Arlington. The limited analysis suggested that red light running crashes decreased but that rear-end crashes (where a following vehicle strikes the rear of a leading vehicle) increased after the cameras were installed.

Because of time constraints, the 2005 study could not answer several operational questions, two of which are listed here:

1. Did the increase in rear-end crashes and decrease in red light running crashes seen in Fairfax County occur in the other five jurisdictions where cameras were operational for at least 1 year (i.e., Alexandria, Arlington, Fairfax City, Fairfax County, Falls Church, and Vienna)?

2. Was the use of the cameras associated with a net change in crash severity? In theory, crash severity is the total amount of injury sustained in all crashes crash. In practice, crash severity may be measured by either (1) tabulating the number of injury crashes (under the presumption that all injury crashes have equal severity) or (2) summing medical and other costs resulting from these crashes (under the presumption that such costs accurately reflect injury severity).

The study presented in this report sought to provide the answers to these questions.

Methods

The methodology for the current study entailed several steps, three of which are noted here:

1. Collect and verify crash and operational data for the six jurisdictions that operated red light cameras in Virginia.

2. Determine the impact of cameras on rear-end and red light running crashes.

3. Determine the net change in crash severity with the use of the cameras.

Six crash types were studied in detail, two of which are emphasized here:

1. *rear-end crashes,* those where VDOT's crash database (VDOT, 2006) shows the crash as collision type 01, meaning the front of a following vehicle strikes the rear of a leading vehicle

2. *red light running crashes,* those where VDOT's crash database (VDOT, 2006) shows the driver action as code 21, meaning a driver was charged with the specific offense of "disregard stop/go light."

Four increasingly sophisticated levels of analysis provided information about the impact of camera installation on the frequency of crashes:

1. the paired *t*-test
2. analysis of variance (ANOVA)
3. generalized linear modeling (GLM)
4. the empirical Bayes (EB) approach.

Each level of analysis has a unique set of advantages; e.g., the paired *t*-test is the easiest approach to understand and can be replicated by hand, whereas GLM excels in controlling for confounding factors. (Confounding factors are changes in the dataset that are beyond the control of the researcher that may cause the experiment to yield erroneous results. For example, if a camera is installed at the same time the yellow interval is lengthened, then a simple before-after comparison of crashes may not accurately indicate the impact of the camera because any change in crashes might also be attributable to the change in the yellow interval. In this example, the yellow interval is a confounding factor.)

The four statistical methods were applied to the dataset, which included more than 3,500 crashes over a 7-year period (1998–2004 inclusive) at 28 intersections with cameras and 44 intersections without cameras in the Northern Virginia jurisdictions of Alexandria, Arlington, Fairfax City, Fairfax County, Falls Church, and Vienna. Essential assumptions concerning the dataset and statistical methods are detailed in the report and outlined in the "Frequently Asked Questions Addressed in This Report" section in this Executive Summary.

Because camera installation was associated with increases in rear-end crashes and decreases in red light running crashes, the net safety impact of the cameras was determined using two approaches:

1. *Determine the effect of the cameras on the number of total injury crashes.* This approach presumes that *each injury crash has the same severity*. Although the approach has value in its simplicity, the assumption of equal severity may be questioned given the common view that angle crashes are somewhat more severe than rear-end crashes. (Angle crashes are those crashes in VDOT's crash database (VDOT, 2006) coded as collision type 02, meaning the front of a vehicle strikes the side of another vehicle. Almost all red light running crashes are coded as angle crashes.)

2. *Determine the effect of the cameras on the severity of angle and rear-end crashes by using comprehensive crash cost as a measure of crash severity.* This approach uses the comprehensive crash costs developed for the Federal Highway Administration (FHWA) by Council et al. (2005). These costs include damage to vehicles and other property, costs from providing emergency medical services (EMS), medical costs, productivity losses, and "monetized quality-adjusted life years." Costs are based on speed limit (either 45 mph and above or below 45 mph), location type (e.g., signalized intersection), and crash type (rear-end or angle). This approach, therefore, assumes that injury crashes may have different severities.

Findings

Impacts on Crash Frequency

- *After cameras were installed, rear-end crashes increased* for the entire six-jurisdiction study area. Usually the statistical methods used in this study showed a statistically significant increase in each jurisdiction. After controlling for time and traffic volume at each intersection, rear-end crash rates increased by an average of 27% for the entire study area.

- *After cameras were installed, red light running crashes decreased* for the entire six-jurisdiction study area. In most cases, the statistical methods used in this study showed a statistically significant decrease in most jurisdictions. After controlling for time and traffic volume at each intersection, red light running crash rates decreased by 42% for the entire study area.

- *However, for Arlington and Vienna, the trends were different than those for the other four jurisdictions.* After controlling for time and traffic volume at each intersection, red light running crash rates increased at the four Arlington County camera intersections and rear-end crash rates decreased at the two Vienna camera intersections. The study did not discern whether the variation was due to different practices that jurisdictions may have followed for operating the cameras (such as possible differences in the methodology for choosing camera sites) or the fact that Vienna had a smaller dataset than most of the other jurisdictions.

- *After cameras were installed, total crashes increased. The reason for this increase is that in general—whether cameras are present or not—there are more rear-end crashes than red light running crashes.* For the entire study area, there was about 4.4 times more rear-end crashes than red light running crashes. Table ES1 shows that even though red light running crash rates decreased more than rear-end crash rates increased after the cameras were installed, the crash rate for all crashes (red light running, rear-end, etc., combined) increased by about 12% because of the considerably larger number of rear-end crashes.

Table ES1. Camera Site Crash Rates Normalized by Time and Total Average Daily Traffic[a]

Jurisdiction	Rear-end Crashes		Red Light Running Crashes	
	Before Camera	**After Camera**	**Before Camera**	**After Camera**
Alexandria	419[b]	536	28	0
Arlington	410	487	187	263
Fairfax City	438	695	500	175
Fairfax County	1463	2023	453	252
Falls Church	130	58	67	38
Vienna	417	369	25	5
Total	3277	4168	1260	733
Change	27% increase		42% decrease	

[a]Average daily traffic (ADT) is the average daily traffic volume entering the intersection.
[b]Rates in Table ES1 and Appendix C are defined as crashes per million ADT per intersection-year, where *ADT* was the number of entering vehicles on a *single* day and *intersection-years* was the duration of the period. For example, a camera was installed at one intersection in Alexandria in March 2004. Thus, there were 6.17 before intersection-years (January 1, 1998, through February 28, 2004) and 0.83 after intersection-year (March 1, 2004, through December 31, 2004). During the before period, the weighted total ADT was 34,823 and 90 rear-end crashes occurred. The before-camera rear-end crash rate for Alexandria was thus (90 x 1 million)/(34,823 ADT x 6.17 intersection-years) = 419.

Impacts on Net Injury Severity

Injury crashes are any type of crash where the crash resulted in at least one injury as reported by the officer on the scene. After cameras were installed, their impact on the number of total injury crashes was too close to call at a superficial level of analysis, but the more advanced methods suggested that the *number of injury crashes* did increase. Even this question, however, does not completely address the impact of cameras on *injury severity*. Accordingly, the approach of using FHWA comprehensive crash costs was emphasized in this analysis. The findings were as follows (see Table ES2):

- *When the impacts of all rear-end and angle crashes were monetized and the officer's indication of crash severity was not used, the cameras were generally associated with a negative safety impact in three jurisdictions.* In one jurisdiction, the impact was positive or negative depending on whether the crashes were normalized by time or by traffic volume. In two jurisdictions, the impact was positive (although in one—Alexandria—the analysis was based on only one site).

- *When the officer's indication of crash severity was used, the cameras were associated with a positive impact in four jurisdictions and a negative impact in two, regardless of whether results were normalized by time or by average daily traffic (ADT).*

Table ES2. Comprehensive Crash Cost Analysis: Summary of Results[a]

Jurisdiction (1)	Results Normalized by (2)	Officer's Indication of Crash Severity Not Used: Crashes with Injury (3)	Officer's Indication of Crash Severity Not Used: Crashes Without Injury (4)	Officer's Indication of Crash Severity Not Used: All Crashes (5)	Officer's Indication of Crash Severity Used: All Crashes Based on KABCO (best guess) (6)[b]	Officer's Indication of Crash Severity Used: All Crashes Based on KABCO (alternative) (7)[c]
Alexandria	Time	224,902	–72,945	151,957	90,555	130,557
	ADT	16,812	–7,201	9,611	4,421	8,022
Arlington	Time	–257,267	–68,828	–326,095	–140,883	–317,420
	ADT	–11,419	–3,353	–14,772	–5,180	–15,666
Fairfax City	Time	142,957	–299,921	-156,964	31,956	–175,354
	ADT	8,676	–16,895	–8,219	10,258	–9,830
Fairfax County	Time	–538,219	–390,049	–928,268	–2,944,295	–3,240,056
	ADT	–13,786	–13,661	–27,447	–123,542	–149,082
Falls Church	Time	–67,771	44,036	–23,735	14,094	–17,087
	ADT	–4,252	4,659	407	3,845	918
Vienna	Time	94,796	–19,038	75,758	92,367	57,342
	ADT	9,748	–944	8,804	10,140	7,270
All Jurisdictions	Time	–400,602	–806,745	–1,207,347	–2,856,206	–3,562,018
	ADT	5,779	–37,395	–31,616	–100,058	–158,368
Average[d]	Time	–$13,814	–$27,819	–$41,633	–$98,490	–$122,828

[a]Dollar amounts represent the safety impact assuming costs for various crash severities for changes in angle and rear-end crashes following camera installation. A positive amount suggests the cameras are associated with a positive safety impact, and a negative amount suggests the cameras are associated with a negative safety impact.
[b]Links KABCO and Virginia severities as follows: 1 = K, 2 = A, 3 = B, and 4 = C.
[c]Links KABCO and Virginia severities as follows: 1 = K, 2 = B, 3 = B, and 4 = C.
[d]Average is based on dividing the total impact (normalized by time) by 29 (as there were 29 intersections).

- *Despite these two findings, aggregation of all jurisdictions showed that the cameras were associated with a much more negative impact when the officer's indication of crash severity was used than when it was not used.* The reason for this discrepancy is that three fatal crashes—the only ones that occurred during the study—caused Fairfax County's crash cost to become a very large, negative number because of the high cost of fatal crashes.

- *When the impacts of injury-only crashes were monetized, the cameras were associated with a net negative impact in three jurisdictions and a net positive impact in three jurisdictions.* The fatal crashes in Fairfax County cannot be ignored, and thus they are included in this dataset. There are, however, generally two reasons for not placing too much emphasis on fatal crashes relative to injury crashes in any safety study. First, the difference between a fatal crash and an injury crash may be attributable to other factors, such as the occupant's health prior to the crash, the use of safety restraints, the crashworthiness of the vehicle, or the occupant's position in the vehicle, in addition to the impact of the camera. Second, there are far fewer fatal crashes than injury crashes. In this portion of the analysis in particular, there were 3 fatal crashes of a total of 1,168 injury crashes.

- *When the three fatal crashes were removed from the analysis and the officer's indication of severity was used (enabling the use of injury severity indices A, B, and C), the cameras were associated with a net positive impact on injury crashes as shown in Table ES3.* The reason for the discrepancy between Table ES3 (where cameras were associated with a beneficial impact on injury crashes by reducing comprehensive crash costs by $513,324) and Table ES2 (where cameras were associated with an adverse impact on injury crashes by increasing comprehensive crash costs by $400,602) is that in Table ES3, different costs associated with each rear-end and angle crash were used based on the level of injury severity for the crash, whereas in Table ES2, a single cost level was used for each rear-end and angle crash, regardless of severity.

- *Since there were 29 intersections involved in the study, the annualized comprehensive crash cost was either a comprehensive crash cost reduction of $17,701 per intersection-year (Table ES3) or a comprehensive crash cost increase of $13,814 per intersection-year (Table ES2).* In essence, the impact of cameras on injury severity is extremely sensitive to assumptions—much more so than the impact of cameras on the number of red light running crashes or rear-end crashes.

Table ES3. Modified Net Change in Comprehensive Crash Cost with the Three Fatal Crashes Removed

Jurisdiction	Injury Crashes Only (A+B+C)	All Crashes (A+B+C+O)
Alexandria	163,500	90,555
Arlington	–72,054	–140,883
Fairfax City	331,877	31,956
Fairfax County[a]	8,539	–381,510
Falls Church	–29,941	14,094
Vienna	111,403	92,367
Total	513,324	–293,421
Average per intersection-year	$17,701	–$10,118

[a]The three fatal angle crashes that occurred in Fairfax County were removed from the analysis. The results are normalized by time.

Conclusions

Five conclusions may be drawn based on the interpretation of data from Virginia's six photo-red programs for the years 1998 through 2004 inclusive. These conclusions do not necessarily reflect data from other states' programs.

1. *Generally, after cameras were installed, rear-end crashes increased and red light running crashes decreased.* Although the manner in which these are tabulated may yield different estimates of the magnitude of the increase or decrease, the change noted is statistically significant and is not attributable to chance.

2. *The impact of cameras on injury severity is too close to call.* After camera installation, the following changes in the comprehensive crash cost were noted, regardless of whether the results were normalized by time or by ADT:

   - Regardless of whether or not the officer's indication of crash severity is used, the cameras were associated with a net *positive* benefit for some jurisdictions (Alexandria and Vienna) and a net *negative* benefit for other jurisdictions (Arlington and Fairfax County) when all crashes (injury and non-injury) were considered.

   - The cameras were associated with a net *positive* benefit for some jurisdictions (Alexandria, Fairfax City, and Vienna) and a net *negative* benefit for others (Arlington, Fairfax County, and Falls Church) when only injury crashes were considered.

   - The cameras were associated with a net *negative* impact when results for all six jurisdictions and all crashes (injury and non-injury) were combined; i.e., the increase in costs from the increase in rear-end crashes more than offset the reduction in costs from the decrease in red light running crashes.

   - The cameras were associated with a net *negative* benefit for all jurisdictions (except Falls Church) when only non-injury crashes were considered.

   - The cameras were associated with either a net *positive* or a net *negative* benefit when results for all six jurisdictions were combined and injury-only crashes were considered. The benefit was negative if all injury crashes were treated as equally severe and the results were normalized by time; normalization by ADT yielded a modest positive benefit. The benefit was positive if the officer's indication of severity (e.g., injury severity ratings A, B, and C) was used provided that the three fatal (K) crashes were removed from consideration.

3. *Even within a jurisdiction, results among intersections varied*. In Fairfax County, for example, total injury crash rates decreased at four intersections and increased at five. The greatest decreases (e.g., 40% at Route 7/Carlin Springs and 41% at Lee Jackson Highway/Rugby Middle Ridge) contrasted sharply with the greatest increases (62% at Leesburg/Dranesville and 256% at Route 236/Heritage).

Based only on the study results presented herein and without referencing other studies, the study did not show a definitive safety benefit associated with camera installation with regard to all crash types, all crash severities, and all crash jurisdictions. The study did show a net safety benefit for some jurisdictions (such as Vienna or Alexandria) but not for others (such as Arlington). There is evidence to suggest that this difference might have more to do with variation among intersections than among jurisdictions. Finally, it may be said that the cameras were associated with a clear decrease in red light running crashes and a clear increase in rear-end crashes.

Recommendations

Summary

Two recommendations are summarized here and detailed on the pages that follow.

1. *Red light cameras should not be implemented without an intersection-specific study of the intersection's crash patterns and geometric characteristics.* Table ES4 gives examples of how to interpret these characteristics to determine whether or not to install a camera at a particular intersection.

2. *Because of the opportunity to identify the geometric and operational characteristics of intersections that could adversely affect the safety impacts of red light cameras, it is recommended that additional controlled studies be conducted at those intersections where red light cameras have been installed.* Two strategies for conducting this necessary additional research are given.

Statewide legislation (HB 1778) allows localities, at their discretion, to use one red light camera per 10,000 residents (Virginia General Assembly Legislative Information System, 2007). However, because the results of this study show that the characteristics at specific intersections may affect the effectiveness of the cameras, additional research is still warranted. The intent of Recommendation 2 is that any entity—state, regional, or local—that chooses to establish a photo-red program should participate in a carefully controlled experiment to monitor the crash impacts of the program and use the results to identify the geometric and traffic characteristics that positively or negatively affect the impact of the implementation of the red light cameras.

Full Text of Recommendations with Implementation Examples

1. *Red light cameras should be implemented on a case-by-case basis and only after a careful review of the crash patterns (rear-end crashes, red light running crashes, and injury crashes) and geometric/operational characteristics (e.g., approach speeds, intersection visibility, signing, and driveways) at each intersection where they are placed.* Two important results led to this recommendation: Within some jurisdictions, at certain intersections and for some crash types, the cameras were shown to be associated with beneficial effects. Examples are decreased red light running crashes in Fairfax City and Fairfax County and decreased comprehensive crash costs in Alexandria and Vienna. On the other hand, when red light cameras were installed at some intersections, they were shown to be associated with a reduction in safety. Further, when the data from all intersections were combined into a single dataset, cameras were not found to be associated with a reduction in injury crashes and comprehensive crash costs. Table ES4 illustrates how this recommendation may be implemented.

Table ES4. Examples for Implementing Recommendation 1

Situation	Resolution
Elected officials in City A suggest that red light cameras be installed, but the city has insufficient staff to study each intersection.	City A may decide not to install red light cameras until engineering staff can be hired.
At Intersection B, the mainline has a speed limit of 45 mph and observed speeds of 55 mph. There is limited red light running and some rear-end crashes.	The jurisdiction may decide not to install red light cameras because they are generally associated with an increase in rear-end crashes and an increase in such crashes at speeds of 55 mph might dramatically increase injury risk.
At Intersection C, the number of rear-end crashes has remained constant over the past 5 years but red light crashes have increased significantly. An engineering study shows that sight distances exceed those prescribed in the standard guidelines, that the 12-inch signal heads are clearly visible, and that the length of the yellow plus all red phase exceeds the recommendations of the Institute of Traffic Engineers (1999).	The jurisdiction may decide to install red light cameras at this location but monitor the crash results closely by measuring the number of rear-end and red light running crashes every month. In addition, engineers visit the site for 1 hour each month to observe driver behavior.
After 6 months with the camera installed at Intersection C, rear-end crashes have increased significantly. Site visits reveal that many of the crashes occur on the eastbound approach during the morning rush hour where a leading vehicle brakes sharply at the onset of the yellow indication and a trailing vehicle strikes the lead vehicle.	The jurisdiction stations a visible law enforcement officer 800 feet upstream of the intersection during the morning rush hour to reduce tailgating before the intersection. The jurisdiction also posts larger red light camera signs 1,000 feet upstream of the intersection. Staff also monitor the intersection during the morning peak hour, checking whether any of the following contributes to the increase in rear-end crashes:: (1) heavy sunlight making the signal difficult to see, (2) heavy trucks obscuring the signal, and (3) commercial driveways within 300 feet of the signal.
Same situation as Intersection C except that resources for additional funds and an engineering study are not available.	The jurisdiction may discontinue the program at this intersection.
At Intersection D, 20 injury crashes have occurred over the past 3 years: 12 were red light running, 4 were rear-end, and 4 were run-off-the-road crashes. In addition, 30 non-injury rear-end crashes have occurred over the past 3 years, suggesting a rate of 5 such crashes every 6 months. No deficiencies (intersection sight distance, signal head visibility, yellow timing, presence of commercial driveways within 300 feet of the intersection) are noted in a site-specific study.	The jurisdiction tentatively initiates a program but only after finding that all 4 run-off-the-road crashes involved alcohol and not poor visibility at the intersection. The jurisdiction carefully monitors rear-end crashes over the next 6 months, recognizing that based on previous data in the previous period, roughly 5 non-injury rear-end crashes might be expected. If a substantially higher number (say, 7) is noted in the first 6 months, even if the rear-end crashes are non-injury, the intersection should be studied again.
At Intersection E, red light running crashes are increasing. Law enforcement officers cannot safely stop red light runners because of heavy congestion at the intersection.	Several safety countermeasures are considered, including traditional law enforcement, adjustments to the signal timing, and installation of a red light camera. It is found that a longer yellow time is warranted. Thus, the yellow time is lengthened. No red light cameras are installed.
At Intersection E, red light running crashes continue to occur 6 months after the length of the yellow time was extended.	The city decides to install and monitor the impact of a red light camera system.
At Intersection F, red light running crashes are increasing. Law enforcement officers cannot safely stop red light runners because of heavy congestion at the intersection.	As with Intersection E, several safety countermeasures are considered. An engineering study as per Recommendation 1 yields no geometric defects (such as poor signal visibility or an insufficient yellow time). Thus, a red light camera is installed.

2. *Because of the opportunity to identify the geometric and operational characteristics of intersections that could adversely affect the safety impacts of red light cameras, it is recommended that additional controlled studies be conducted at those intersections where red light cameras have been installed.* This additional research may be accomplished using Strategy A and/or Strategy B:

   - *Strategy A: Determine whether the improved safety at the seven specific intersections listed in Appendices B and C was definitively associated with the use of the cameras.* After cameras were installed at these intersections, total injury crashes decreased, red light running crashes decreased, and rear-end crashes either decreased or moderately increased. Because the cameras were eliminated after June 30, 2005, it may also be possible to determine if the safety benefits degraded at these intersections. The research should compare the characteristics of these intersections with those of others in the study where the cameras were associated with a net negative effect. These seven intersections are:

     — Lee Jackson Highway and Fair Ridge Drive (Fairfax County)
     — Lee Jackson Highway and Rugby/Middle Ridge (Fairfax County)
     — Leesburg Pike and Westpark/Gosnell (Fairfax County)
     — Route 7 and Carlin Springs (Fairfax County)
     — West Broad Street and Cherry Street (Falls Church)
     — Maple Avenue East and Follin Lane (Vienna)
     — Route 123 and North Street (Fairfax City) (where the rear-end crash rate increased more than at the other six intersections but injury rates still decreased).

   - *Strategy B: Conduct a carefully controlled experiment at particular additional intersections that have been selected for the installation of cameras to examine further the impact of red light programs on safety.* Because of the extreme variation in crash history at the various intersections, further data attained through carefully controlled experiments are required to assess definitively the intersection characteristics that influence the effectiveness of red light cameras in reducing the number and severity of crashes and to determine the most beneficial locations for their placement. These data should be collected so that an evaluation may be performed in accordance with generally accepted scientific principles such as the establishment of control sites; the identification of treatment sites that address confounding factors; and the comparison of crash frequency and severity between treatment and control sites. The researchers believe that the use of approximately 24 to 48 intersections, a comparable number of control sites, and 3 to 5 years of data would be sufficient for a scientifically defensible study. This additional research could be conducted by any one of several entities that have an interest in how red light cameras are operated. Such entities include, but are not limited to, an individual jurisdiction, a group of jurisdictions, a regional body such as a planning district commission, a public interest group, a branch of the federal government, a university, a national research funding body such as the National Cooperative

Highway Research Program, or any other entity that seeks to understand better the factors that influence the safety impacts of red light camera programs.

Note that each strategy is designed to identify the reasons red light cameras were associated with adverse safety impacts at some intersections but not others—reasons that have not yet been conclusively identified. If no jurisdictions choose to implement red light cameras, then Strategy A will be more productive. If many jurisdictions choose to implement red light cameras, then Strategy B will be more productive. If some jurisdictions do and some do not choose to implement red light cameras, then a mix of these two strategies should be used.

Frequently Asked Questions Addressed in the Report

The findings of this report are based on controlling for a variety of confounding factors, such as changes in the yellow interval for the traffic signal and drivers' behavioral response after a camera is installed. The statistical methods used to address these factors are outlined in this report. Briefly, the detailed methods sought to address the following frequently asked questions:

1. Did the manner in which crashes were tabulated and normalized affect the findings?

Yes and no. It affects the magnitude of the findings but not the major conclusions drawn. For example, Table ES1 shows the change in crash rates based on summing the intersection crash rates (which had been normalized by volume and ADT), an approach that is consistent with the paired sample *t*-test. This change in crash rates is also shown in the upper row of Table ES5, and the method of computation is shown in footnote *a* of Table ES5. However, had the crash rates been computed by simply summing the crashes at all intersections and then dividing that sum by the sum of the product of each intersection's number of intersection-years and ADT (the method shown in footnote *b* of Table ES5), the crash rates would be different, as shown in the bottom row of Table ES5. However, the overall conclusions do not change: rear-end crashes increase, red light running crashes decrease, and the impact of cameras on injury crashes (when using a simple method of analysis) is too close to call.

2. Why are the crash data presented as crash rates in Table ES1 (and Appendices B and C) rather than as raw crashes?

The data are presented as rates for two reasons. First, the durations of the before/after periods are unequal and vary by intersection; thus, at a glance, the rates are easier to interpret than are the raw data. Second, the easiest statistical method to interpret—the paired *t*-test—estimates the difference between before crashes and after crashes at each intersection. Thus, presentation of the data in the manner done in Table ES1 (or Appendices B and C) is most consistent with the most transparent method of analysis. The raw crash data are available to the public at http://www.vtrc.net/photo_red.

Table ES5. Alternative Methods for Computing Camera Site Crash Rates[a]

Method	Rear-End Crashes	Red Light Running Crashes	Injury Crashes
At each intersection, divide crashes by product of ADT and intersection-years. Sum these rates.[a]	27% increase	42% decrease	10% increase
Sum total number of crashes at all intersections. Divide by sum of product of ADT and intersection-years.[b]	11% increase	24% decrease	3% decrease

[a] For example, Vienna had two intersections. One had a before period of 1.42 years (with 18 rear-end crashes and a total ADT of 40,982), yielding a before rear-end crash rate of 309 per million average daily entering vehicles. Similar computations showed that the same intersection had an after period crash rate of 278 per million average daily entering vehicles. The second intersection had before and after crash rates of 108 and 91, respectively. The percentage change in crash rates for Vienna is thus [(309 + 108) – (278 + 91)]/(309 + 108) = an *11.5% decrease*.

[b] The same two Vienna intersections showed 57 rear-end crashes during the before period. During the before period, the product of the first intersection's ADT and before-period duration (40,982 vehicles x 1.42 before-years = 58,194) may be added to the product of the second intersection's ADT and after-period duration (63,006 vehicles x 5.75 before-years = 362,285) to obtain a total before-period value of 420,480 vehicle units. Thus, the before-period rate is 57/420,480 = 136 crashes per million vehicle units. Similar computations show that the after period rate is 226 crashes per million vehicle units. Thus, the change in crash rates is 226/136 = 1.66, which is a *66% increase*. (Because the term "vehicle units" is both the numerator and denominator of the ratio 226/136, the 66% increase is unitless and is simply, in practical terms, a 66% increase in crashes for a given measure of vehicle exposure.)

3. I am familiar with crash rates. Why are the crash rates presented in Table ES1 so high?

The convention is to divide the crash rates shown in Table ES1 by 365 (to convert from days to years), which would thus yield lower rates than those shown. For example, the rate shown in the footnote to Table ES1 is 419 crashes per million average daily entering vehicles per intersection-year, based on an exposure of only the average ADT from a single day. An alternative approach would be to use an exposure measure based on the product of the ADT and 365 days (in 1 year). Because the numerator (the number of crashes) does not change for either approach, the measure of exposure in the denominator is divided by 365 in the second approach. Thus, a rate of 419 crashes per million average daily entering vehicles per year is equivalent to a rate of 419/365 = 1.15 crashes per million total entering vehicles per year. Because all of the rate comparisons were internal to this study and did not use rates obtained in other studies, the extra step of dividing each rate by 365 was not necessary. To increase the transparency of the computations, the rates used in the statistical calculations, such as those shown in Table ES1 and presented in Appendix C, are used in the sections of this report that refer to the paired *t*-test, ANOVA, the EB approach, and GLM.

4. If you had not included ADT at all as a factor and simply had compared the number of crashes per intersection-year, would the results have changed?

The magnitude would have changed, but the direction of the change would have remained constant. Of the total number of intersections, ADT was available for 23 intersections and was not available for 6 intersections. The simple before-after comparison based only on intersection-years (and not ADT) in Appendix B would still show rear-end crash rates increasing (but by 37% rather than 27%) and would show red light running crash rates decreasing (but by 29% rather than 42%). Injury crash rates would go up by 17% rather than 10%. The differences between these results and those shown in Tables ES1 and ES3 are that 6 additional intersections were used in these results and changes in ADT were not factored into these results.

5. Did a detailed examination of the other crash types, i.e., those other than rear-end and red light running crashes, yield additional insights beyond those discussed here?

No, with one exception. The detailed statistical methods were applied to a total of six crash types: rear-end, red light running, angle, injury, red light running injury, and total crashes. Generally, the findings matched those noted here. The exception was that the results using the EB and GLM methods suggested that the total number of injury crashes increased, although these results must be interpreted carefully. When all jurisdictions were aggregated, the results suggested an injury increase between 8% and 29%, as shown in Table H5 in Appendix H. However, point estimates of the increases in individual jurisdictions using the EB method were either higher than this range (Arlington with an 89% increase, Falls Church with a 79% increase, or Vienna with a 59% increase) or lower than this range (Fairfax City with a 5% decrease or Fairfax County with a 6% increase).

6. Did rear-end crashes tend to decrease as drivers became accustomed to the camera?

No. Based on evidence gathered in one jurisdiction—Fairfax County—no overall trend of a decrease in rear-end crashes was found. Generally, the ratio of rear-end crashes to total crashes did not show a decline in the months following camera installation.

7. Did the police officer's indication of severity change following the installation of the camera?

No. Based on evidence gathered in Fairfax County, a decrease was found, but it may well have been attributable to chance. The reason for this is that for camera intersections in Fairfax County, a Chi-square analysis of the officer's indication of injury severity for rear-end and red light running crashes showed nonsignificant decreases ($p = 0.51$ for belted occupants and $p = 0.27$ for unbelted occupants) following camera installation.

8. Given that the FHWA comprehensive crash costs use a KABCO severity scale and Virginia does not use such a scale, how were the FHWA comprehensive crash costs mapped to Virginia data?

The KABCO severity scale (National Safety Council, 1990) is used to classify injury severity for occupants; it has five categories: K = killed; A = disabling injury; B = evident injury; C = possible injury; O = no apparent injury. Virginia police officers assign injury at the scene of a crash on a scale from 1 to 4, with 1 being a fatality. The following linkage was assumed (1 = K, A = 2, B = 3, and C = 4). For example, FHWA gives a comprehensive crash cost of $84,820 for a rear-end injury crash, KABCO scale A, at an intersection with the speed limit below 45 mph. A Virginia crash for which the officer assigned a severity index of 2 would be given a comprehensive crash cost of $84,820.

9. Is the manner in which the KABCO scale and Virginia's scale were linked (1 = K, A = 2, B = 3, and C = 4) the only manner of performing such a linkage?

No. Although it is fairly clear that 1 = K and 4 = C, it is conceivable that 2 and 3 should both be B.

10. If this alternate method of linking the KABCO scale and the officer's severity scale had been used, would the findings of the study have changed?

Not substantially. Although different manners of linking affect the magnitude of the results, they do not affect the overall findings.

11. Instead of using FHWA comprehensive crash cost data, could Virginia-specific injury data have been used in the study? Thus, if camera installation was associated with an additional rear-end crash at a Virginia intersection, could injury-specific data from that crash have been used rather than the FHWA value?

No. Detailed Virginia-specific injury data, such as the injury severity score, could be obtained for only 3% of total crashes—whereas officers had indicated that an injury had occurred in approximately 38% of total crashes. Thus, based on an examination of the 2001 and 2002 crashes, it would not be appropriate to use detailed injury data since detailed data could be obtained for only a low proportion of crashes (3%) compared to the proportion of crashes for which an officer indicated an injury had occurred (38%).

12. Were traffic volumes missing for any of the sites studied?

Yes. Although major road traffic volumes were available for every site, minor traffic volumes were not available for some sites. For 1 of the 4 Fairfax City camera sites, 3 of the 13 Fairfax County camera sites, 1 of the 3 Falls Church camera sites, and 1 of the 3 Vienna camera sites, only major road traffic volumes were available.

13. Did the unavailability of minor road traffic volumes at some sites affect the findings?

No for the paired *t*-test and ANOVA methods; yes for the GLM and EB methods. Analyses for all four methods were performed with major ADT and then total ADT in Fairfax City. The use of major road ADT as compared to the use of total ADT showed few differences in the paired *t*-test and ANOVA runs. (The use of major ADT instead of total ADT occasionally resulted in a minor shift, such as from a nonsignificant increase to a nonsignificant decrease or from a significant to a nonsignificant decrease.) Using major ADT as opposed to total ADT in the ANOVA runs resulted in variables changing from significant to nonsignificant (or vice versa), but the overall results of the ANOVA were not greatly altered. For the EB and GLM methods, the use of major ADT versus total ADT did cause some differences when there was a small number of sites. Fairfax City was such a case: a major ADT was available for eight sites but a total road ADT was available for only six sites. In that situation, the EB and GLM results yielded different answers depending on whether major ADT or total ADT was used.

14. What approach was followed, then, for the EB and the GLM methods?

To resolve this, when the major ADT would yield a greater number of sites than the total ADT, the major ADT was used for the EB approach. For the GLM procedure, the total ADT was used, with the goal being to take advantage of both the major and minor road traffic information. However, in the case of Fairfax City GLM, two sets of models, one using major ADT and the other using total ADT, were constructed for performing sensitivity analysis, and, ultimately, for Fairfax City, the models with major ADT were used for the GLM analysis.

15. Other than traffic volume, could other factors have confounded the results?

Yes. These include truck percentages, the length of the yellow interval, the number of left-turn lanes, the number of through lanes, and other factors such as the speed limit. These were not addressed with the first level of analysis—the paired sample *t*-test—but they were studied in the GLM, ANOVA, and EB analyses.

16. Your analysis of comprehensive crash costs examined only angle and rear-end crashes. Is it a flaw of the analysis that such a small proportion of the intersection crashes was studied?

Probably not. Based on the number of crashes shown in Table A5 of Appendix A, the rear-end crashes and angle crashes represented 88% of the total intersection crashes which suggests that they are the proper focus of the study. It is conceivable, but unlikely, that the other crash types, such as run off the road, could somehow have been affected by the camera.

17. Your analysis of comprehensive crash costs examined angle crashes, of which red light running crashes are only a subset. Is it a flaw of the analysis that such a large proportion of intersection crashes was studied?

Possibly yes, because although almost all red light running crashes are angle crashes, the converse is not the case; thus, it is conceivable that there were additional angle crashes that had nothing to do with the presence of the camera included in the analysis. However, it is also conceivable that there were rear-end crashes that had nothing to do with the presence of the camera. Although it is possible to identify those angle crashes that are definitively associated with red light running, it is not possible to identify only those rear-end crashes that are definitively related to the presence of the camera (unless the crash reports are examined manually). Thus, a fair comparison would require either comparing all angle and rear-end crashes (Option 1) or comparing only those angle and rear-end crashes directly attributable to the presence of the camera or red light running (Option 2). As shown in Table ES6, Option 2 was not feasible.

Table ES6. Analysis Questions for Comparing Increased Rear-End Crashes and Decreased Red Light Running Crashes[a]

Analysis Question	Option 1: Study all angle and rear-end crashes	Option 2: Study only those angle and rear-end crashes related to red light running and/or presence of camera at intersection
How should angle crashes be tabulated?	Tabulate *all* angle crashes (crash type coded as 02)	Tabulate *only* angle crashes affected by red light running (driver's offense is coded "Disregard Stop/Go light")
How should rear-end crashes be tabulated?	Tabulate *all* rear-end crashes (crash type coded as 01)	Tabulate *only* rear-end crashes affected by presence of camera (no reasonable method of identifying these crashes is possible unless each report is examined manually)
Should this analysis option be selected?	Yes	No

[a]Methods of identifying these crashes are indicated in parentheses.

18. Why did the results for Fairfax County indicate that the cameras were associated with such a negative impact on injury crashes?

Over all six jurisdictions, three fatal crashes occurred after the cameras were installed, and all three were angle crashes in Fairfax County, one of which occurred during the month of camera installation. Because the comprehensive crash cost for a fatal crash is approximately 40 times higher than that of the next highest severity level treating these three crashes as fatal crashes meant they accounted for 85% of the comprehensive crash costs in that jurisdiction. Had the three fatal crashes been removed from the analysis, aggregating all injury crashes across all intersections would suggest the cameras were associated with a positive safety impact when only injury crashes were considered. Table ES3 shows the results of this analysis.

19. An advantage of the EB method is that it controls for otherwise confounding changes over time, such as trends in driver behavior. Yet a corresponding disadvantage is that each independent variable was categorized by year. Some variables, such as the yellow interval, changed in the middle of the year. How was this addressed?

Changes were assumed to have occurred at the nearest full calendar year. For example, if the yellow interval changed to 5 seconds in March 2002, the signal was assumed to have that yellow interval for all of 2002.

20. Could this method of categorizing changes by year have affected the results?

Yes, but not substantially. The impact of this approach was tested by conducting an EB analysis for one crash type in three ways: (1) assuming the yellow interval change occurred at the beginning of the year, (2) assuming the yellow interval change occurred at the beginning of the following year, and (3) rounding the phase change to the closest year. To determine the sensitivity of this rounding, the researchers computed the impact on crashes for one crash type in Fairfax County. The results showed that rounding to the beginning of the current year, rounding to the following year, and rounding to the closest year produced slightly different results, but only by a few percentage points. Because these results were relatively close, this impact was not studied further.

21. Why is the term "cameras were associated with an increase/decrease in crash type x" used throughout the report?

In theory, the four statistical methods cannot prove that one event (camera installation) caused a later event (an increase in rear-end crashes). Instead, the statistical methods can show that when one event occurs, another event also tends to occur and that the occurrence of the second event (if statistically significant) was not due to chance. When reporting the results of the statistical test, it is correct to say that the statistical test shows that the two events tend to occur in tandem. The fact that one event causes another is—in theory—an inference made by the analyst after reviewing the test results.

22. Therefore, would this report have the same meaning if the phrase "is associated with" was replaced with the phrase "is correlated with"?

Yes.

23. Does the term "nonsignificant" used in this report simply mean "insignificant" or "nonsignificant" as shown in other reports or articles?

Yes. The term *nonsignificant* means that a statistically significant difference was not observed at a particular significance level (which is conventionally 0.05). Other sources have described this phenomenon as "statistically insignificant" (Guevara and Ben-Akiva, 2006) or "statistically nonsignificant" (Vingilis et al., 2006).

Costs and Benefits Assessment

This study focused exclusively on the impacts of red light cameras on crashes; it did not estimate other types of impacts, such as the amount of money required to operate a red light camera program. If the spirit of Strategy B in Recommendation 2 is kept—i.e., a carefully controlled experiment to evaluate the impacts of red light cameras on crashes is conducted prior to initiating a program—following the recommendation will yield a cost and benefit.

The cost of such an experiment would have two components: (1) the monetary cost of the experiment and (2) the risk that a program would be established that would increase the risk of crashes. Considering only the first component, with 36 treatment sites, 36 control intersections, and a 4-year data collection period, the cost of the experiment might be estimated as $400,000. Considering the second component, the cost might range from 0 (the cameras did not adversely affect safety where they were deployed on an experimental basis) to as high as $3 million per intersection-year (assuming the very worst case scenario from Table ES2 and assuming cameras adversely affected safety at each intersection).

The benefit of such an experiment would be a better understanding of where red light cameras would be effective and where they would not be effective. This benefit may be roughly quantified by considering two intersections from Fairfax County.

1. At one intersection (Leesburg Pike and Westpark/Gosnell), the cameras were associated with a *reduction* in comprehensive crash costs of $33,416 per intersection-year.

2. At another intersection (Leesburg Pike and Towlston Road), the cameras were associated with an *increase* in comprehensive crash costs of $34,741 per intersection-year.

Based on this knowledge, a red light camera program would be initiated at the Leesburg Pike and Westpark/Gosnell intersection (thereby reducing comprehensive crash costs by $33,416 per intersection-year) but not at Leesburg Pike and Towlston Road (thereby avoiding an increase in comprehensive crash costs of $34,741 per intersection-year).

Another example can illustrate this point further: Suppose that localities are considering the implementation of red light cameras at 50 intersections in Virginia. Suppose further that half of Virginia's intersections are comparable to Leesburg Pike and Westpark/Gosnell, where a camera was associated with improved safety, and suppose that the other half are comparable to Leesburg Pike and Towlston Road, where a camera was associated with decreased safety.

A completely wrong decision would be to perform two actions.

1. *Install cameras at the 25 intersections comparable to Leesburg Pike and Towlston Road.* The cost of installing these cameras (at a location where the cameras are associated with an increase in comprehensive crash costs of $34,741 per intersection-year) would be (25 intersections)($34,741 per intersection-year) = $868,525 per year.

2. *Not install cameras at the 25 intersections comparable to Leesburg Pike and Westpark/Gosnell.* The cost of not installing cameras at these locations (where a camera would be associated with a reduction in comprehensive crash costs) would be (25 intersections)($33,416 per intersection-year) = $835,400 per year.

Thus the total cost of this wrong decision would be $868,525 + $835, 400 = $1,703,925 per year. Relative to this "wrong" decision, the correct knowledge of where to place cameras would save $1,703,925 per year (i.e., the "right" decision would be to place the cameras at the 25 intersections comparable to Leesburg Pike and Westpark/Gosnell but not to place them at the 25 intersections comparable to Leesburg Pike and Towlston Road).

If the results of the experiment proposed in Recommendation 2 (Strategy B) were thus applied at 50 intersections over a 4-year period, the benefits may be estimated as ($1,703,925 per year)(4 years) = $6.8 million over the 4-year period. Clearly, this potential savings is an order of magnitude estimate only. The actual savings might be more or less depending on (1) the number of intersections considered, (2) the percentage of intersections where cameras were beneficial relative to those where cameras were not beneficial, and (3) the extent to which the cost savings for the two intersections chosen for this example represent cost savings at other intersections in Virginia.

FINAL REPORT

THE IMPACT OF RED LIGHT CAMERAS (PHOTO-RED ENFORCEMENT) ON CRASHES IN VIRGINIA

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INTRODUCTION

Red light running, defined as a motorist entering an intersection after the onset of the red signal, caused almost 5,000 crashes, more than 3,600 injuries, and at least 26 deaths in Virginia in 2004. This year was not unique: over the 5-year period of 2000 through 2004, red light running occurred in almost 25,000 crashes in Virginia; such crashes resulted in 99 fatalities and 19,000 injuries (Virginia Department of Transportation [VDOT], 2006).

The true number of crashes related to red light running is quite possibly higher than 25,000 over the 5-year period. In VDOT's crash database (VDOT, 2006), which was the source of the Virginia crash data, a crash in which one or more drivers are charged with "disregarded stop-go light" is designated a red light running crash. In some cases, a driver may not be charged with this offense, even though a red light running violation did occur. Thus, the frequency of red light running crashes, injuries, and fatalities may indeed be greater than the data initially suggested.

Across the United States each year, more than 800 people are killed and 200,000 are injured in crashes caused by red light running (Retting et al., 1999; Retting and Kyrychenko, 2002). In addition, the Insurance Institute for Highway Safety (2000) reported that more than half of those persons killed in such crashes were not in the vehicle with the motorist who ran the red light.

The Photo-Red Enforcement Alternative

Photo-red enforcement programs address this problem of red light running. The technology consists of a camera that photographs the license plates of vehicles that enter an intersection after the signal has turned red. The system, which allows for a specified grace period after the light has turned red, automatically records relevant information such as the time and date of the violation, the speed of the offending vehicle, the license plates, and the time elapsed after the onset of the red signal. After a process of review and validation, approved citations are sent along with photos of the violation to the registered owner of the vehicle. These systems have been labeled red light cameras, photo-red enforcement, automated enforcement, or several other terminologies; this report refers to the technology as *photo-red enforcement*.

Studies of photo-red enforcement have identified a crash reduction benefit, specifically for angle crashes (Retting and Kyrychenko, 2002; Ruby and Hobeika, 2003). Other studies have questioned the efficacy of the programs, noting that they either increase or do not reduce crashes (Andreassen, 1995; Burkey and Obeng, 2004). A study conducted for the Transportation Research Board determined that these programs have potential but that more information is necessary for a complete evaluation (McGee and Eccles, 2003). In addition, several studies emphasized the presence of confounding factors and the difficulty of isolating the effects of the cameras (Fox, 1996; Mann et al., 1994). A detailed literature review of photo-red enforcement programs was provided by Garber and Miller (2005).

Recent Virginia Findings

In Virginia, seven jurisdictions operated photo-red enforcement programs at some point during the 10-year period when they were temporarily permitted in some jurisdictions: the cities of Alexandria, Fairfax, Falls Church, and Virginia Beach; the counties of Arlington and Fairfax; and the Town of Vienna. With the exception of Virginia Beach, which did not institute its program until 2004, the programs were studied in the fall of 2004 (Garber and Miller, 2005), and the report of the study resolved several questions concerning Virginia's programs. The analysis focused on the technical, fiscal, and operational feasibility of photo-red enforcement.

Red light camera programs passed the test of technical feasibility. The systems work properly, and case law strongly indicates the programs pass legal muster in the three key areas: privacy, equal protection, and due process (Garber and Miller, 2005). Public opinion surveys indicate that roughly two-thirds of respondents (more than 500 people in six locations in Virginia) favor photo-red programs, and 80% believe the programs can improve safety.

Fiscal feasibility pertains to the financial costs of the program from the viewpoint of the agency operating the program. Three comparison categories were used in the 2005 study to assess the annual financial impact of the programs: revenue/cost ratio, annual net revenue, and net revenue per citation. The revenue/cost ratios ranged from 0.62 (Vienna) to 1.03 (City of Fairfax). The annual net revenues ranged from a loss of $97,811 (Fairfax County) to a gain of $12,499 (Arlington). The net revenue per citation differed from a loss of $29.45 per citation (Vienna) to a gain of $1.33 per citation (City of Fairfax). Thus, the photo-red programs were not a large revenue generator, since three jurisdictions lost money on the program, one broke even, and two showed a modest profit.

Operational feasibility considers the impact of the photo-red program on crashes and citations. The cameras were associated with an average reduction of 19% in citations per intersection for the four jurisdictions where reliable citation data were obtained. The cameras were further associated with an increase in rear-end crashes and a reduction in angle crashes in one jurisdiction, Fairfax County, where a detailed study considered not only crashes but also other confounding factors such as number of through lanes and left-turn lanes, length of yellow interval, mainline traffic volume, and speed limit. In a basic crash analysis considering only time and volume, the cameras were associated with an increase in rear-end crashes and a decrease in red light running crashes in three of the jurisdictions: Fairfax County, Fairfax City, and Vienna.

Due to time constraints, the 2005 report could not answer three operational questions, two of which were already noted in the Executive Summary:

1. Did the increase in rear-end crashes and decrease in red light running crashes seen in Fairfax County occur in the other five jurisdictions where cameras were operational for at least 1 year (i.e., Alexandria, Arlington, Fairfax City, Fairfax County, Falls Church, and Vienna)?

2. Was the use of the cameras associated with a net change in crash severity? In theory, crash severity is the total amount of injury sustained in all crashes crash. In practice, crash severity may be measured by either (1) tabulating the number of injury crashes (under the presumption that all injury crashes have equal severity) or (2) summing medical and other costs resulting from these crashes (under the presumption that such costs accurately reflect injury severity.)

3. How did use of the cameras affect the frequency of other types of crashes, such as total crashes and injury red light running crashes?

The third question takes on heightened importance when, in jurisdictions such as Fairfax, there is an increase in one type of crash and a decrease in another type of crash because it is believed that different crash types are not necessarily associated with the same injury severity.

PURPOSE AND SCOPE

The purpose of this study was to answer the three operational questions. Alternatively stated, the study sought to determine the impacts of Virginia's red light cameras on crashes and to determine whether they were associated with a net positive or net negative safety impact based on data obtained from the jurisdictions of Arlington County, the City of Alexandria, the City of Fairfax, Fairfax County, the City of Falls Church, and the Town of Vienna.

To determine the associated net safety impact of photo-red enforcement, the research had three objectives:

1. *To determine the impact of cameras on rear-end crashes, red light running crashes, angle crashes, injury red light running crashes, total injury crashes, and total crashes.* This objective was met by tabulating crashes in each of the six Northern Virginia jurisdictions where data were available.

2. *To ensure that the observed changes were not confounded by other factors coincident with camera installation (such as traffic volumes, changes in signal timings, the presence of heavy trucks, the length of the yellow interval of the traffic signal, and geometric characteristics).* This objective was met by applying several statistical tests to the available data: paired *t*-test, analysis of variance (ANOVA), generalized linear modeling (GLM), and the empirical Bayes (EB) method.

3. *To determine whether the cameras were associated with a net increase or decrease in the injury severity of crashes.* This objective was met by examining the severity of the crash indicated by the officer and the estimated comprehensive cost for each crash.

The scope of this research was limited to data found for these jurisdictions for the 7-year period January 1, 1998, through December 31, 2004. Further, the study focused exclusively on the camera's impacts on crash frequency, crash severity, and crash rates Other aspects of red light cameras resolved in the 2005 report (Garber and Miller, 2005), such as citation history, legal issues, public opinion, and fiscal impacts to the jurisdictions operating photo-red enforcement, were not addressed in this study. In particular, the scope of the study did not include the impact of the cameras on citations or the ability of law enforcement to apprehend motorists who run red lights. (In the 2005 study, it was noted in the initial survey responses that the cameras could be used at intersections where it was otherwise unsafe to cite motorists who ran a red light.)

METHODS

Four iterative steps comprised the methodology used to achieve the study objectives:

1. Collect and verify crash and operational data for the six jurisdictions that operated red light cameras in Virginia.

2. Determine the impact of cameras on crash types.

3. Determine the net change in comprehensive crash costs so as to identify the change in overall crash severity with the use of the cameras.

4. Conduct sensitivity tests to determine the validity of the assumptions made about the data.

Collect and Verify Data

Site data, crash data, operational data, and geometric data were obtained for each jurisdiction that operated photo-red enforcement for at least 3 years. These data were sought for January 1, 1998, through December 31, 2004, which, for signals in most jurisdictions, reflected periods before and after the cameras were installed. Upon collection and synthesis of these data, the data files were sent to localities for verification on November 3, 2005, and were made available at www.vtrc.net/photo_red. A draft report was sent to the six jurisdictions for review on May 30, 2006.

Site Data

Site data included data from sites with cameras and from those without cameras. Camera installation dates varied by jurisdiction and within jurisdictions. Camera intersections and the dates of installation were provided by officials in each jurisdiction. In some cases, a camera was installed at an intersection prior to January 1, 1998. Because of the absence of "before" data, that intersection was not included in any of the analyses. The jurisdictions also identified comparison intersections, which are intersections where cameras were never installed but that have characteristics similar to those of the camera intersections. For Fairfax County, the researchers used the list of comparison sites recommended by VDOT staff who were familiar with a previous study of Fairfax County's photo-red program (BMI, 2003). Finally, the researchers identified spillover sites, which were intersections within 0.6 mile of a camera intersection. Among the six jurisdictions, 15 spillover sites were selected. All of the spillover sites were located in four of the jurisdictions (Fairfax City, Fairfax County, Falls Church, and Vienna) because no suitable spillover sites could be identified in Arlington or Alexandria. The tables in Appendix A provide a list of the camera, comparison, and spillover intersections included in this study. (Note that although four Alexandria cameras are shown, only one was installed after January 1, 1998—the starting point for the "before camera" period. Similarly, although seven Fairfax City cameras are shown, only five were installed after January 1, 1998. Thus only one Alexandria site and only five Fairfax City sites had both before and after data.)

Crash Data

Crash data included all crashes within 150 feet of the intersection at each study site. The crash data included the crash document number, intersection location, date of the crash, crash type, driver action, and injury severity. Six crash types were considered in this report:

1. *rear-end crashes,* those where VDOT's crash database (VDOT, 2006) shows the crash as having collision type 01, meaning that the front of a following vehicle strikes the rear of a leading vehicle

2. *angle crashes,* those where VDOT's crash database (VDOT, 2006) shows the crash as having collision type 02, meaning the front of a vehicle strikes the side of another vehicle

3. *red light running crashes,* those where VDOT's crash database (VDOT, 2006) shows that the driver action had code 21, meaning a driver has been charged with the specific offense of disregard stop/go light

4. *injury red light running crashes,* those where VDOT's crash database (VDOT, 2006) shows the driver action had code 21 *and* the crash resulted in at least one injury

5. *total injury crashes,* those where the crash resulted in at least one injury

6. *total crashes,* any reported crash.

In this study, all reportable crashes were included. Reportable crashes are those where there has been an injury or fatality or where the property damage was at least $1,000. In Fairfax County, crashes were extracted from VDOT's Oracle Database (VDOT, 2006) by referencing the individual intersections. However, crashes that occurred within incorporated towns and cities and within Arlington County could not be accessed directly by location. Therefore, for these jurisdictions, researchers searched all crashes for the entire jurisdiction to extract the crashes at the desired intersections.

Operational Data

Operational data included the date (if any) of *camera* installation at the site; the *major ADT* (defined as the average daily traffic [ADT] on the major approach of the intersection); the *minor ADT* (defined as the ADT on the minor approach of the intersection); the *total ADT* (defined as the ADT on both the major and minor approaches of the intersection); the *ITE difference* (defined as the difference between the length of the yellow plus red interval calculated using the equation recommended by the Institute of Traffic Engineers [ITE] [1999] and the actual duration of this interval at the intersection); and the *truck percentage* (defined as the percentage of trucks in the traffic stream). The ADT and truck percentage data were extracted from annual publications of ADTs by VDOT's Traffic Engineering Division (see, e.g., VDOT [1999]). In the event the ADT was not available for an intersection for a given year, the ADT was interpolated using the known ADTs. Camera installation dates and historical data on the length of the yellow interval were provided by the individual jurisdictions.

Geometric Data

Geometric data included for the intersection were (1) whether or not a frontage road was present; (2) whether the intersection was a T-intersection or a four-way intersection; and, for the major approach only, six additional data elements: (3) whether curb cuts were present, (4) the number of through lanes, (5) the number of left-turn lanes, (6) the speed limit, (7) the design speed, and (8) the grade. VDOT's GIS Integrator provided aerial photos of each intersection, which provided some data such as the number of through lanes and left-turn lanes. Other data, such as the design speed, were obtained through officials from each jurisdiction.

Estimate the Impact of Cameras on Crash Frequency

Four increasingly sophisticated levels of analysis provided information about the impact of cameras on the frequency of crashes: paired *t*-test, analysis of variance (ANOVA), generalized linear modeling (GLM), and empirical Bayes (EB) analysis. The most basic level—the paired *t*-test—is advantageous because it can be quickly interpreted; its disadvantage is that it does not control for confounding factors. The most advanced level—the EB analysis—has advantages and disadvantages that are the reverse: it controls for confounding factors but is more labor-intensive to perform and evaluate.

Paired *t*-Test

At the first level, paired sample *t*-tests were conducted for each jurisdiction for each of the six crash types. The jurisdictions were divided into two groups: camera sites and non-camera sites. In addition, paired sample *t*-tests were conducted for the spillover sites, for which the before and after periods were determined by the installation date at the referenced camera site. The first paired *t*-test considered the change in crash rates normalized by time, which gives the results in crashes per intersection-year. The second paired *t*-test considered these crash rates normalized by total ADT, which included the major and minor road ADTs. (Thus, the second paired *t*-test used the number of crashes divided by the product of the number of intersection-years and the total ADT.)

Analysis of Variance

The second level of analysis used ANOVA to determine which main effects (i.e., a single variable such as high speed limit) and which second-order interaction effects (i.e., the combination of two variables such as high ADT and high speed limit) are useful for understanding the impact of red light cameras on crash types. The first ANOVA considered the operations variables plus a single site identifier variable, as shown in Table 1. Because each site identifier variable was unique (e.g., the first site had a value of 1, the second site had a value of 2, and so on), the single site identifier variable represents the geometric characteristics of each intersection.

The second ANOVA included the operations variables but replaced the single site identifier variable with multiple geometric variables, shown in Table 2. ANOVA was conducted for each jurisdiction separately and for the entirety of Northern Virginia (i.e., all jurisdictions combined).

The software package used for ANOVA, Statistical Package for the Social Sciences (SPSS), calculated second-order interaction for a maximum of 10 variables. In the second ANOVA, 12 variables were considered, and so 2 variables were forcibly omitted from the second-order interaction calculations. For each jurisdiction and each crash type, an ANOVA was run that considered the main effects of all 12 variables. The *p*-values were then reviewed, and the two variables that had the largest *p*-values were omitted in the calculation of second-order interactions. The second ANOVA, therefore, considered the main effects of all 12 variables and the second-order effects of 10 variables. For jurisdictions with a small number of

Table 1. Operations Variables and Single Site Identifier Variable Used in First ANOVA

Variable Name	Description
Camera	Camera at intersection (no; yes)
Major ADT	ADT on the major road (0-35,000 vehicles; 35,001-60,000 vehicles; greater than 60,000 vehicles)
Total ADT	ADT on the major road plus the ADT on the minor road (0-43,000 vehicles; 43,001-70,000 vehicles; greater than 70,000 vehicles)
ITE Difference	Yellow interval difference at the major road defined as: ITE Difference = Existing yellow interval + Grace period – Yellow interval calculated from ITE recommended equation (less than or equal to 0.5 sec; greater than 0.5 sec)
Truck Percentage	Percentage of trucks in traffic stream on major road (1-2%; 3-4%; greater than 4%) Percentages are given as whole numbers only
Site Identifier	1…*n* (each jurisdiction had *n* intersections)

Table 2. Geometric Variables Used in Second ANOVA[*a*]

Variable Name	Description
Frontage Road	Frontage road present or not (no; yes)
T Intersection	T intersection or not (no; yes)
Curb Cuts	Presence of any curb cuts at the intersection (no curb cuts; at least 1)
Through lanes	Sum of the number of through lanes present in both directions of the major road (4 or less; 5 or more)
Left-turn lanes	Sum of the number of left-turn lanes present in both directions of the major road (none; 1 or 2; 3 or more)
Speed Limit	Posted speed limit on the major road (40 mph or less; 45 mph or greater)
Design Speed	Design speed of the major road (less than 35 mph; 35-45mph; more than 45 mph)
Grade	Grade of the major road (0 = 3% or less, 1 = 4% or greater)

[*a*]Note that the single site identifier variable in Table 1 was replaced with multiple geometric variables.

intersections, *p*-values were often available for only a handful of the 12 variables because of the lack of variation in the independent variables. In those cases, the second ANOVA considered the main and two-way interactions of those variables for which *p*-values were able to be calculated in the first ANOVA.

Rear-end crashes in Fairfax County can be considered an example of the second ANOVA process. The results of ANOVA with the main effects of all 12 variables are shown in Table 3. The variables with the largest *p*-values in the "*p*-Value" column are T Intersection and Through Lanes. Therefore, the second ANOVA considered the main effects of all 12 of these variables and the two-way effects of 10 variables (omitting T Intersection and Though Lanes). Thus, this two-way analysis necessarily involves a total of 57 variables: the main effects of the 12 variables from Table 3 plus the 45 combinations of two-variable effects that can be extracted from Table 3.

ANOVA's strength is that it uses a classic experimental approach to determine which main effects and which second-order interaction effects are significant. Its weakness is that it presumes the crash data follow a normal distribution; in contrast, crash data are believed to follow the negative binomial distribution. Thus, although ANOVA has value as a screening instrument for determining *which* variables merit further examination, it is not the best approach for quantifying the *exact impact* of these variables.

Table 3. Main Effects for Rear-end Crashes Determined by Analysis of Variance

Variable	*p*-Value
Camera	0.419
Total ADT	0.000
ITE Difference	0.438
Truck Percentage	0.002
Frontage Road	0.003
T Intersection	0.904[a]
Curb Cuts	0.670
Through Lanes	0.948[a]
Left-turn Lanes	0.000
Speed Limit	0.017
Design Speed	0.212
Grade	0.234

[a]The two variables with the highest *p*-values were excluded from the second-order calculations of the analysis.

Generalized Linear Modeling

The third level of analysis, GLM, provides a way to establish a quantitative relationship between operations and geometric characteristics and the number of crashes. The paired *t*-tests (first level of analysis) are helpful only in showing whether or not the presence of a red light camera at a particular intersection was associated with a statistically significant increase in the number of crashes. Further, they ignore the effects of confounding factors that could have affected the crash numbers. ANOVA (second level of analysis) shows which of the variables and the interaction terms are most likely affecting the crashes but not how they affect the crashes. GLM addresses these issues while evaluating the effect of cameras on crashes.

The reason for choosing GLM over simple linear regression should be noted. Simple linear regression is inappropriate because it assumes a normal distribution for the dependent variable, i.e., number of crashes. However, the number of crashes over a set of different sites does not necessarily follow the normal distribution but instead may follow the Poisson or negative binomial distribution (Hauer, 1997; Persaud and Lord, 2000). GLM, which is an extension of traditional simple linear modeling, allows the dependent variable to follow any of the distributions in the exponential family, including the negative binomial distribution. A logarithmic function was used to describe how the mean of the dependent variable is related to the linear combination of variables (SAS Institute, 1999). A typical GLM equation would be of the form:

$$\begin{aligned}&\text{Expected number of crashes (for a crash type)}\\&= \exp(\alpha + \beta_1 \times \text{Main effect 1} + \beta_2 \times \text{Main effect 2} + \beta_3 \times \text{Main effect 3}\\&+ \beta_4 \times \text{Interaction effect 1} + \beta_5 \times \text{Interaction effect 2})\end{aligned} \quad \text{[Eq. 1]}$$

where α = constant or intercept term, and β_1 *to* β_5 = coefficients or parameters for the main and interaction effects.

The analysis initially considered all 12 variables and the 66 two-way interactions as the set of available independent variables. Of these, a "best subset" of independent variables had to be selected through a process of "variable selection," which would result in the best crash models. A method of backward elimination was employed for the variable selection. (Backward elimination, which has been used for linear regression models [Kutner et al., 2005], appeared to be useful for the research team's application of GLM.) The backward elimination technique begins with an initial model that contains all the available variables. The variable having the coefficient with the highest *p*-value in the model is eliminated, and the model rebuilt with the remaining variables. This process is repeated until the number of variables is reduced to a predefined number or the model satisfies predetermined criteria. In GLM, instead of building models that have a set number of independent variables at the end of backward elimination, the objective was to obtain a final model in which all the parameters are statistically significant (conventionally *p*-values less than 0.05) and the model itself has a high Akaike information criterion (AIC) value. However, for some jurisdictions and crash types where the dataset was either small or did not have substantive variation, this conventional threshold of for *p* had to be raised above 0.05. The AIC is a measure of goodness of the models and is given by:

$$\text{AIC} = l(\hat{\theta}) - q \qquad \text{[Eq. 2]}$$

where $l(\hat{\theta})$ is the maximum log likelihood value of the model, and q is the number of parameters in the model (Zhang and Ivan, 2005). Using AIC penalizes the maximum log likelihood value of a model with the number of parameters in the model, and hence two models with different number of parameters can be compared by this criterion. The variables in the final model obtained by such a procedure are those among the entire set that best predict the number of crashes. (Although it has been suggested that instead of maximizing the AIC shown in Eq. 2, one should minimize the negative value of Eq. 2, both approaches will yield the same result.)

Since the GLM models are to be used to quantify the effect of the presence of the cameras on crashes, the camera variable is forced to stay in the model during the process of backward elimination. As a consequence, the final models will not be the same as those that would be obtained when the camera variable is not forced, and they are optimal only for quantifying the effect of cameras on crashes while accounting for confounding factors. This methodology is applied to develop crash models for each crash type and jurisdiction, from which the effect of cameras on each crash type in each jurisdiction is estimated.

If the camera has no interaction effects, the coefficient of the camera variable (for the camera's main effect) represents the change: a negative camera coefficient means that the camera is associated with crash reduction, and a positive camera coefficient means that the camera is associated with an crash increase. If there is an interaction effect between the camera variable and another independent variable in the final model, then the effect of the camera is found by summing the value of interaction effect and the main effect for an appropriate value of the variable with which the camera interacts.

A correlation analysis was performed to look for possible correlations between the camera variable and the other independent variables. The results of this analysis are summarized in Table 4. Usually, there is not a strong correlation between the camera variable and the other

Table 4. Pearson Correlation Coefficients Between the Camera Variable and the Remaining Independent Variables

Other Independent Variables	Camera				
	Arlington	Fairfax City [a]	Fairfax County	Falls Church	Vienna
Year	0.40	0.22	0.30	0.48	0.27
MajorADT	0.10	-0.15	0.21	0.04	0.10
TotalADT	0.20	0.05	0.20	-0.04	-0.19
ITEDiff	-0.16	0.39	0.23	-0.31	*b*
Truck	-0.13	-0.01	-0.20	-0.19	-0.01
Frontage	0.39	0.38	0.28	*b*	0.76
Tintersection	-0.01	-0.43	0.06	-0.20	*b*
CurbCuts	-0.20	-0.16	-0.03	-0.31	*b*
ThruLanes	0.11	0.14	0.03	*b*	*b*
LTLanes	-0.03	-0.14	-0.14	0.09	-0.76
SpeedLimit	0.12	-0.44	-0.09	*b*	*b*
DesignSpeed	0.12	0.18	0.36	*b*	*b*
Grade	0.52	-0.16	-0.11	*b*	*b*

[a]Fairfax City results are based on Adjustment Technique A. In Fairfax City only, cameras were installed in May 1998, yielding only 4 months of "before" data. Adjustment Technique A discarded the data from May through December 1998 and thus the after period was January 1999 through December 2004.
[b]The Pearson correlation coefficient could not be calculated because of the lack of variability in the independent variable for that jurisdiction.

independent variables, and usually there is not a consistent degree of correlation between each variable and the camera across all jurisdictions. The only possible exception is the presence of frontage roads, which was weakly correlated with the presence of camera in three jurisdictions (Arlington, Fairfax City, and Fairfax County) and somewhat strongly correlated with the presence of the camera in a fourth jurisdiction (Vienna).

Considering that 78 terms could potentially be included in the model and that a model was developed for each crash type in each jurisdiction, backward elimination with all 78 terms was prohibitively time-intensive. ANOVA was used to delineate the important terms that would be used as input for the backward elimination procedure. Using ANOVA and the Statistical Analysis System (SAS) software, p-values of the 78 variables were calculated for each crash type and jurisdiction. All variables having a p-value higher than 0.2 were rejected. The value of 0.2 was chosen to satisfy the competing criteria of obtaining an adequate number of variables for the backward elimination while ensuring that the elimination procedure did not have too many variables such that it would be unwieldy. The categories were consistent for all jurisdictions, as shown in Tables 1 and 2. In most jurisdictions, either because of the small size of the individual datasets or because of insufficient variation among the independent variables, ANOVA for different crash types did not produce enough variables that satisfied the criterion (p-values less than 0.2). Subsequently, ANOVA was run with data from all of the jurisdictions together. The variables satisfying the p-value criterion from the overall ANOVA and the individual jurisdiction ANOVA for a particular crash type were combined and used for backward elimination for that crash type in that jurisdiction.

The final GLM models were chosen by iteratively maximizing Eq. 2 through the elimination of nonsignificant variables from the models. The PROC GENMOD function in the SAS software was used for creating these models (PROC GENMOD uses maximum likelihood estimation of parameters to fit models based on the data). Initially, a model was built with the small subset obtained from ANOVA. The variable whose coefficient had the highest *p*-value was eliminated from the model, and the model was then rebuilt. Usually, this process continued until all variables remaining in the model had a *p*-value less than 0.05, the model itself had a high AIC value, and further elimination of variables would not result in a higher AIC value. However, it was not always possible to have a model that only had *p*-values less than 0.05, as was the case with some of the models for Vienna where some variables had *p*-values greater than 0.05. Except in some cases where the camera variable had a high *p*-value even after the backward elimination, a variable with a *p*-value greater than 0.50 was not included in the model for any jurisdiction. (The camera variable was always forced into the model.) In other jurisdictions, in contrast, it was possible to develop models where no *p*-value exceeded 0.0001. In general, larger datasets resulted in models that had lower *p*-values (and such models are considered to be better than models with higher *p*-values). SAS does not give the AIC value directly; rather, it gives the maximum log likelihood that in conjunction with Eq. 2 (Zhang and Ivan, 2005) yields the AIC.

In the procedure described, the *p*-value of the coefficient with the highest *p*-value (other than camera) present in the model decreased as nonsignificant variables were removed in each step of the backward elimination. In some cases, the *p*-value of the variable having the highest *p*-value in the final model was quite small (e.g., it was 0.0001 for Fairfax County injury crashes, which was a large dataset). In other cases, especially for smaller datasets, the *p*-values were relatively large (e.g., 0.48 for Falls Church injury red light running crashes). These "highest *p*-values" of the final models are a measure of the quality of the final models and are dependent on factors such as the size and quality of the dataset, which varied from jurisdiction to jurisdiction and crash type to crash type. These highest *p*-values for each crash type in the jurisdictions are given in Table 5. For the analysis in Table 5, the total ADT was used instead of the major ADT for constructing GLMs for each crash type in all the jurisdictions. (As is discussed later in the report, the analysis for Fairfax City was redone using major ADT.)

Empirical Bayes Method

The EB method constituted the fourth level of analysis. This technique has gained popularity in the past decade and has been well documented in multiple references (Hauer, 1997; Persaud et al., 2000). Two features of the EB analysis are noteworthy in the context of this study. The first is that the EB process increases precision in safety estimation by correcting for the regression-to-mean bias that arises because of non-random selection of treatment sites. For example, cameras are most often placed at those intersections with a higher number of crashes. Second, the EB analysis presumes a negative binomial distribution that is generally accepted to be the distribution crashes follow.

Using internally developed spreadsheet applications, the EB approach employs a crash estimation model calibrated from before data at camera sites and before and after data at comparison sites. The crash estimation model predicts the number of crashes that would have occurred at camera intersections had the camera not been installed. The general form of the crash estimation model is given in Eq. 3 and shows six independent variables.

Table 5. Highest *p*-Value for Model Coefficients Other Than Camera Coefficient

Jurisdiction	Crash Type	*p*-Value[a]
Arlington	Rear-end	0.018
	Red Light Running	0.019
	Angle	0.000
	Injury Red Light Running	0.165
	Injury	0.000
	Total	0.000
Fairfax City[b]	Rear-end	0.071
	Red Light Running	0.010
	Angle	0.002
	Injury Red Light Running	0.078
	Injury	0.140
	Total	0.044
Fairfax County	Rear-end	0.038
	Red Light Running	0.118
	Angle	0.008
	Red Light Running w/ Injury	0.093
	Injury	0.000
	Total	0.013
Falls Church	Rear-end	0.309
	Red Light Running	0.009
	Angle	0.026
	Injury Red Light Running	0.359
	Injury	0.080
	Total	0.059
Vienna	Rear-end	0.001
	Red Light Running	0.475
	Angle	0.055
	Injury Red Light Running	0.148
	Injury	0.356
	Total	0.003

[a]Each model may have one or more variables, and each variable has a coefficient with a particular *p*-value. The highest *p*-value in each model is reported in this column.
[b]GLM analysis for Fairfax City used Adjustment Technique A with total ADT. In Fairfax City only, cameras were installed in May 1998, yielding only 4 months of "before" data. Adjustment Technique A discarded the data from May through December 1998, and thus the after period was January 1999 through December 2004.

Crashes that would have occurred without camera installation (π)

$$= \alpha_y (Volume)^b (Speed)^c (Yellow)^d (Trucks)^e (Through\ lanes)^f \ (Left\ lanes)^g \qquad \text{[Eq. 3]}$$

where α_y = calibration parameter associated with a specific year (1998 through 2004)

b, c, d, e, f, g = calibration parameter associated with a geometric or operational variable

Volume = ADT for the major road or the major plus minor road

Speed = speed limit on major road in miles per hour

Yellow = difference between yellow interval recommended by ITE and actual yellow interval

Trucks = percentage of trucks in major road traffic stream

Through lanes = number of lanes on major road approach

Left lanes = total number of left-turn lanes from both major approaches.

At a specified site, there may be other factors that could affect crash frequency, but the effect of these factors is unknown or is not explicitly modeled in the equation. Such factors may include weather conditions, economic conditions, vehicle technologies, and changes in driver behavior. The α_y term in the model accounts for these other factors and their yearly changes. Along with α_y, the model parameters (b, c, d, e, f, and g) are estimated using the maximum log likelihood as coded in the spreadsheet applications. Then, the model is used to predict the number of crashes that would have occurred had no camera been installed. These predicted crashes are shown as π in Eq. 4.

To determine the impact of the cameras on safety, a comparison is made between actual crashes (λ) and predicted crashes (π). The essence of the comparison is that it compares crashes that did occur given that a camera was installed (the actual crashes) and the crashes that would have occurred had no camera been installed (i.e., the modeled crashes from Eq. 3). This ratio may intuitively be described as an index of effectiveness (θ), where a value of less than 1.0 indicates that the treatment improved safety. For example, if θ is computed as 1.41, it can be said that crashes increased by 41%. Note that θ is not the exact ratio of actual to predicted crashes because the variance of these predicted crashes, as shown in Eq. 4, is used to provide an unbiased estimate of θ.

$$\theta = (\lambda/\pi)/\{1+\mathrm{Var}(\pi)/\pi^2\} \qquad \text{[Eq. 4]}$$

Empirical confidence intervals are used to determine whether this point estimate is statistically significant. For example, if the confidence bounds for this point estimate were 1.29 and 1.52, it can be said that although 41% is the best estimate of θ, it is likely that the true point estimate is between 29% and 52%. If the confidence bounds contain 1.0, the safety impact is not significant and the treatment had no measurable effect.

For each jurisdiction and each crash type analysis, at least one EB test was performed. For Fairfax County, major ADT was available for all 46 sites. For 40, both major and minor road ADT (referred to as total ADT in the remainder of this report) were available. For that jurisdiction, two EB runs were performed. One run used all 46 sites with major ADT only, and one run used 40 sites with total ADT. Fairfax City, Vienna, and Falls Church similarly had a few sites where minor road ADT was not available such that one of two options had to be chosen: (1) using all sites (but relying on major ADT only) or (2) using a smaller number of sites (and thus having the total volume at those sites). Because the number of sites with total volumes in those jurisdictions was 6 or fewer (less than the number of covariates in Eq. 3), major ADT was used to increase the sample size. An additional EB test for Fairfax City using total ADT (with 6 sites) and compared to major ADT (using 8 sites). For Arlington County, all sites had major and minor ADT, and thus for that jurisdiction, total ADT was used. In addition to the EB test for each jurisdiction, the results from all five jurisdictions were aggregated into a single dataset, and this dataset used major ADT to facilitate comparisons across all sites.

Summary of Rationale for Four Levels of Analysis

The researchers employed four levels of analysis to satisfy the diverse audiences for this work. No method is perfect, and each method has advantages and disadvantages. The paired sample *t*-test is a simpler analysis, and so it is easily performed and most easily understood. It also allows readers to digest the actual data used in the analysis quickly and thus can most easily be replicated by interested parties. However, *t*-tests assume that the data are normal, whereas crashes often follow a Poisson or negative binomial distribution (Hauer, 1997; Persaud and Lord, 2000).

The more complex methods (ANOVA, GLM, and EB) account for confounding factors that may influence the results. ANOVA is a classic experimental approach and is widely accepted among persons familiar with experimental design, but not necessarily among those who conduct crash analysis because of its reliance on the normal distribution. GLM assumes neither a normal distribution nor the categorization of continuous data but does require the analyst to decide on a structural approach for developing the models. Given that the main effects and two-way interaction effects of the variables shown in Table 3 would yield a total of 78 variables in the expression, clearly some rigorous procedure for choosing which of these effects requires greater study is desired. The EB approach has the benefit of the support of the traffic research community and is considered by some experts to be the best method when used correctly. GLM and the EB method provide practical results, but they are labor- and time-intensive.

Compute Camera Impacts on Net Change in Comprehensive Crash Costs So As to Identify the Change in Overall Crash Severity

When all crash types increase (or decrease) after the cameras are installed, it is possible simply to examine the net change in crashes to determine whether there is an associated positive or negative safety impact. However, when some crash types increase and other crash types decrease, there are two feasible methods for estimating the net severity impact based on available data in Virginia. One assumes that injuries of a given crash category (such as angle crashes at an intersection with a speed limit of less than 45 mph) are equally severe. The other uses the officer's indication of crash severity at the scene of the crash to identify a particular injury severity level with each crash. These two methods may be described as follows:

- *Method 1:* Use average costs *regardless of severity level* to monetize the crash impacts of photo-red enforcement at each intersection. FHWA computed a comprehensive crash cost for reported angle injury crashes, angle non-injury crashes, rear-end injury crashes, and rear-end non-injury crashes at various speed limits (Council et al., 2005). Comprehensive crash costs include damage to vehicles and other property, costs from providing emergency medical services (EMS), medical costs, productivity losses, and "monetized quality-adjusted life years." Costs are based on speed limit (either 45 mph and above or below 45 mph), location type (e.g., signalized intersection), and crash type (rear-end or angle). These crashes represent most (88%) of the crashes that occurred at the various intersections, and costs for these crashes are shown in Table 6.

Table 6. FHWA Comprehensive Crash Costs without Injury Severity

Speed Limit	No Injury		Injury Severity Unknown	
	Rear-end	Angle	Rear-end	Angle
<= 45 mph	$11,463	$8,673	$44,120	$47,639
>= 50 mph	$5,901	$8,544	$58,458	$45,148

- *Method 2:* Use average costs *for different severity levels* to monetize the crash impacts of photo-red enforcement. FHWA has computed a more detailed comprehensive crash cost for the aforementioned crash types based on the KABCO scale (Council et al., 2005). For example, there is a cost for rear-end injury crashes with Severity Level A that is different from the cost for rear-end injury crashes with Severity Level C. These costs are detailed in Table 7. The KABCO severity scale (National Safety Council, 1990) is used to classify injury severity for occupants; there are five categories: K = killed; A = disabling injury; B = evident injury; C = possible injury; O = no apparent injury. Virginia does not use the KABCO scale but does use a 1 to 4 scale for an officer's indication of crash severity, which may be linked to the KABCO scale as indicated in Table 8.

Table 7. FHWA Comprehensive Crash Costs with Injury Severity

Speed Limit	K[a]		A		B		C	
	Rear-end	Angle	Rear-end	Angle	Rear-end	Angle	Rear-end	Angle
<= 45 mph	$4,614,214[a]	$4,090,042	$84,820	$120,810	$39,398	$46,660	$39,398	$46,660
>= 50 mph	$4,541,549	$4,025,777	$76,587	$182,177	$32,761	$53,195	$32,761	$53,195

[a]The FHWA report did not have a rear-end crash cost estimate for code K at the <=45 mph speed limit category. Therefore, the percentage differential (12.81%) between the cost of a rear-end crash and an angle crash in the >= 50 mph speed limit category was used to calculate this missing cost estimate. Therefore, the cost of an angle crash at the <=45 mph speed limit category ($4,090,042) was increased by 12.81% to calculate the cost of a rear-end crash ($4,614,214).

Table 8. Summary of Options for Using FHWA Comprehensive Crash Costs[a]

Basis for Estimating Comprehensive Crash Cost	Computational Methods	Rationale
1. Use FHWA average costs for injury crashes and average costs for non-injury crashes	Determine costs for injury crashes (assume severity is unknown) and non-injury crashes; sum the results	Requires less data, uses no assumptions about Virginia's injury scale, and is easily replicable
2. Link KABCO scale with Virginia severity scale (1-4)	Let 1 = K, 2 = A, 3 = B, and 4 = C	Uses additional information provided by officer; provides most unbiased estimate of crash costs
3. Link KABCO scale with Virginia scale but bias toward lower injury severity	Same as above, except assume 2 = B (thus 1 = K, 2 = B, 3 = B, and 4 = C)	Provides estimate of crash costs under assumption that actual injury severities are lower than Virginia officers rate them

[a]FHWA comprehensive crash costs are available in Council et al. (2005).

The Virginia FR 300 police report classifies injury type sustained in an automobile crash into five categories:

1. dead before report made
2. visible signs of injury, as bleeding wound or distorted member; or had to be carried from scene
3. other visible injury, such as bruises, abrasions, swelling, limping, etc.
4. no visible injury but complaint of pain or momentary unconsciousness
5. fatality after report made.

The only instance of Category 5 was at Route 50 and Pershing Drive in Arlington, which is a comparison site. Therefore, the traditional scale of 1 to 4 was used. The KABCO scale includes all fatalities that occur within 18 months of the crash, and VDOT's crash database (VDOT, 2006) includes all fatalities that occur within 12 months of the crash. (As discussed in Appendix I, there was a very small proportion of injury crashes—3 of 1,168—where the officer did not indicate any severity level.)

Note that in Method 2, an assumption regarding how Virginia's injury severity scale (1, 2, 3, or 4) reported at the scene of the crash matches with the KABCO scale is required. Accordingly, this method could be performed using any one of three options. There are three options because there are three ways to link the KABCO and Virginia scales as shown in Table 8. The first option directly links the KABCO scale to Virginia's 1 to 4 scale. The second option links the two scales in the following manner: 1 = K, 2 = B, 3 = B, and 4 = C; this option would bias the costs toward lower injury severity, as shown in Table 8. (The rationale for this option is to imagine that there is not much difference between Virginia Levels 2 and 3 and to assume that they have the lesser severity of B on the KABCO scale; note that A on the KABCO scale is not used in this linkage.) The third option links the two scales such that the costs are biased toward greater injury severity. However, the FHWA crash costs for rear-end and angle crashes based on the KABCO scale assign the same dollar value to Level B and Level C crashes (Council et al., 2005). Therefore, linking the two scales by 1 = K, 2 = A, 3 = B, and 4 = B would produce the same results as the original method (1 = K, 2 = A, 3 = B, and 4 = C). To avoid duplication, the first two options shown in Table 8 were used in the analysis.

For each method (i.e., Method 1 where severity is not used at all or Method 2 where three options for using severity are given in Table 8), the comprehensive crash cost associated with the camera at a given intersection may be shown as either a benefit (positive dollar amount, indicating a savings in comprehensive crash costs associated with implementation of cameras) or a loss (negative dollar amount, indicating an increase in comprehensive crash costs associated with implementation of the cameras). Conceptually, this comparison is made by comparing crash frequency at each intersection before and after camera installation.

However, the before and after camera periods are not directly comparable because their duration and their traffic volumes differ. To make the two periods comparable, the crash cost analysis was normalized by time and traffic volume, making each a measure of exposure.

- To normalize by time, the comprehensive crash cost of rear-end and angle crashes was divided by the duration of the period such that a net comprehensive crash cost *per intersection-year* was computed for the before and after periods.

- To normalize by traffic volume, the comprehensive crash cost of rear-end and angle crashes was divided by the number of vehicles entering the intersection annually such that a net crash cost *per million entering vehicles* was computed for the before and after periods.

Conduct Sensitivity Tests to Test Assumptions

No dataset is perfect, and thus the investigators had to make assumptions regarding the use of the data set. Eight key assumptions were made. Some pertained to how the analysis should be conducted, and some pertained to the availability of data. The latter pertained to the use of traffic volume, signal timing, the law enforcement officer's indication of injury severity at the crash scene, the use of national data instead of Virginia-specific data to evaluate net injury severity, the continuity of any observed increase in rear-end crashes, and the impact of safety restraints on injury severity.

These assumptions and the sensitivity tests used to test them are summarized in Table 9 and discussed here.

1. For the paired t-test and ANOVA, it is better to use fewer sites for which major and minor road ADTs are available than it is to use more sites for which only major road ADT is available. Major road ADTs were available for all sites, but minor road ADTs were available for only 80% of the sites. Therefore, the before-after paired *t*-tests and ANOVA were done in two ways. First, ANOVA was completed using all sites with the major ADT. Then, ANOVA was completed using only the sites for which both minor and major road ADTs were available.

2. For the GLM and EB analyses, when the number of sites is small, it is better to have more sites (and thus use major ADT) than fewer sites (and thus use total ADT). When the number of sites is large, the use of either major ADT or total ADT will suffice. As noted previously, every site will have a *major ADT*, which is the ADT on the major approach. Most of those sites will also have a *minor ADT* (the ADT on the minor approach). For those sites, a *total ADT* (sum of the major and minor ADTs) may be used. However, at some sites, the minor ADT will not be available, meaning that only a major ADT can be used. Thus, a decision must be made: Should a large number of sites with only major ADT or a smaller number of sites with total ADT be used? For the small Fairfax City dataset, GLM and EB analyses were performed for the crash types using major ADT (8 sites), and then a second GLM analysis was performed that included total ADT (6 sites). These GLM and EB analyses were performed twice, first using Adjustment Technique A and then using Adjustment Technique B. In contrast, for the large

Table 9. Summary of Eight Assumptions Made and Description of Sensitivity Tests Conducted to Test Them

No.	Assumption	Description of Sensitivity Tests
1	For the paired *t*-test and ANOVA, it is better to use fewer sites for which major and minor road ADTs are available than it is to use more sites for which only major road ADT is available.	• For Fairfax City, conduct paired *t*-test twice: once with major ADT only and once with total ADT. • For Fairfax City, conduct ANOVA twice: once with major ADT only and once with total ADT.
2	For the GLM and EB analyses, when the number of sites is small, it is better to have more sites (and thus use major ADT at each) than fewer sites (and thus use total ADT). When the number of sites is large, the use of either total ADT or major ADT will suffice.[a]	• For Fairfax City, conduct GLM twice: once with major ADT only and once with total ADT. Similarly, conduct EB analysis twice. (Fairfax City has a small number of sites.) • For Fairfax County, conduct EB analysis twice: once with major ADT and once with total ADT. (Fairfax County has a large number of sites.)
3	For Fairfax City, Adjustment Technique B should be used with GLM and Adjustment Technique A should be used with EB analysis.	• For Fairfax City, conduct GLM with major ADT twice: once with Adjustment Technique A and once with Adjustment Technique B. Similarly, conduct EB analysis twice. Compare results for consistency.
4	When the yellow interval is changed at any point during a year, the change should be indicated as occurring either at the beginning of the current year or at the beginning of the next year (based on the month in which the change was made).	• For Fairfax County, conduct EB analysis where if a signal changes at any point in year *x,* it is assumed that change applies to entire year *x.* • For Fairfax County, conduct EB analysis where if a signal changes at any point in year x, it is assumed that change applies only to next year *x* + 1.
5	The best way to link the Virginia injury scale and the KABCO injury scale is as follows: 1 = K, 2 = A, 3 = B, and 4 = C.	• Compute comprehensive crash cost assuming 1 = K, 2 = A, 3 = B, and 4 = C. • Compute comprehensive crash cost assuming 1 = K, 2 = B, 3 = B, and 4 = C.
6	For estimating comprehensive crash costs as shown in Table 8, it is better to use national data than Virginia-specific data because there are too few Virginia crashes to comprise a reliable dataset.	• Determine number of Virginia crashes for which EMS data are available. • Determine number of Virginia crashes for which detailed injury data are available for 2001 through 2002.
7	If a camera is associated with an increase in the number of rear-end crashes, the number of rear-end crashes will not revert to the number prior to camera installation	• In Fairfax County, examine proportion of rear-end crashes by month after camera installation. If proportion remains constant, the assumption holds.
8	The severity of any injury crashes that occur does not change after camera installation.	• In Fairfax County, compare distribution of injury severity for injury crashes before and after camera installation. • Repeat analysis for injury crashes where safety restraints were used and for injury crashes where safety restraints were not used.

[a] *Small number of sites* is where the number of sites is similar to the number of independent variables in the model. Thus, if six independent variables are in the model (as was the case with Fairfax City and Fairfax County), a small number of sites would be about 6. *Large number of sites* is where the number of sites is many times the number of independent variables in the model. Thus Fairfax County (which had 46 such sites) may be considered to have a large number of sites.

Fairfax County dataset, the EB analysis for each of the six crash types was performed using major ADT (46 sites) and total ADT (40 sites).

3. For Fairfax City, Adjustment Technique B should be used with GLM and Adjustment Technique A should be used with EB analysis. In Fairfax City only, cameras were installed in May 1998, yielding only 4 months of before data. Although the 4-month before period (January through April 1998) could be converted to an annualized value, the question remained as to how to treat the 6 years and 8 months of after data given that the spreadsheet applications could accommodate only 6 after years. Two adjustment techniques were compared. Adjustment Technique A discarded the data between May and December 1998, thus yielding an after period from January 1999 through December 2004. Adjustment Technique B converted the May through December 1998 data to an annual figure and then used that annual data plus the data through December 2003, thereby excluding the data from January through December 2004.

4. When the yellow interval is changed at any point during a year, the change should be indicated as occurring either at the beginning of the current year or at the beginning of the next year (based on the month in which the change was made). For example, if a yellow interval changed to 5 seconds in March 2002, the signal was assumed to have that yellow interval for all of 2002. In gathering the operational data, some jurisdictions showed cases where the length of the yellow interval at an intersection was changed in the middle of the year. One such jurisdiction was Fairfax County. The EB approach considers intersections and the variables on a yearly basis; thus the question arose regarding which yellow interval to use for the analysis. Therefore, the EB method was run twice for one set of Fairfax County data: once with the ITE difference assumed to start at the beginning of the year and once with the ITE difference assumed to start at the end of the year.

5. The best way to link the KABCO scale and Virginia's injury scale is as follows: 1 = K, A = 2, B = 3, and C = 4. As discussed earlier, the Virginia FR 300 police report provides injury severity information on a 1 to 4 scale. In contrast, the FHWA report (Council et al., 2005) linked detailed injury information from hospitals and EMS personnel to the KABCO scale used by police officers in the other states where FHWA's research was undertaken. There was some ambiguity about how to link Virginia's system (1, 2, 3, and 4) and the KABCO scale. Therefore, the injury severity calculations were performed for two variations of linking the scales: one used the option shown here and one used the following pairing: 1 = K, 2 = B, 3 = B, and 4 = C. Table 8 summarized these methods.

6. For estimating comprehensive crash costs as shown in Table 8, it is better to use national data than Virginia-specific data because there are too few Virginia crashes to comprise a reliable dataset. Table 8 illustrated the use of nationally derived comprehensive crash costs for injury or non-injury angle or rear-end crashes. It was questioned, however, whether there were sufficient data to perform an analysis based on Virginia-specific injury data instead of national data. Accordingly, the investigators obtained from VHI, Inc., all detailed injury data that were available for crashes that occurred in 2001 through 2002 and determined the number of crashes for which detailed injury data were available. These data include total hospital charges, length of stay, Abbreviated Injury Scale (AIS) (Trauma.Org, n.d.a), Injury Severity Score (ISS) (Trauma.Org, n.d.b), and whether a patient was transported from the scene of the crash by EMS personnel for crashes at select signalized intersections in the Northern Virginia jurisdictions of Alexandria, Arlington, Fairfax City, Fairfax County, Falls Church, Prince William, and Vienna for the period 2001 through 2002. VHI, Inc., is the contractor for the Virginia Crash Outcomes

Data Evaluation System (CODES) effort and as part of its work has obtained detailed injury data for crashes that occurred during the 2-year period 2001 through 2002.

7. If a camera is associated with an increase in the number of rear-end crashes, the number of rear-end crashes will not revert to the number prior to camera installation. During the course of the study, an additional question was raised pertaining to the exact impact of red light cameras on rear-end crashes. It was suggested that the observed increase in rear-end crashes might be temporary since drivers may grow accustomed to the camera. Accordingly, the following question was posed: After a camera is installed, do rear-end crashes continue to increase or do they eventually drop as drivers adjust to the cameras?

Figure 1 suggests that a simple look at the graph of rear-end crashes over time will not necessarily provide an easy answer because of the seemingly large variation in the dataset. Figure 1 shows the number of rear-end crashes per month at one intersection, and the large spikes make discernment of a trend difficult. There are two possible sources of these spikes: random variation and external factors.

The random variation in the dataset can be minimized by carefully choosing the number of periods, the period length, and the number of intersections studied. In the case of Figure 1, the length of the period contributes to this random variation because the short period length of just 1 month means that small numbers (between 0 and 3 crashes) occur in each period. Although longer periods, such as 1 year, would have larger numbers of crashes and thus less variation, the number of periods would then be too small to discern a trend. (For example, computation of the number of crashes per year for a camera installed in 2004 would be inappropriate because the after period would have only two data points.) By increasing the number of intersections from 1 to 13, however, there can be large numbers of crashes each period and sufficient numbers of periods to discern a trend.

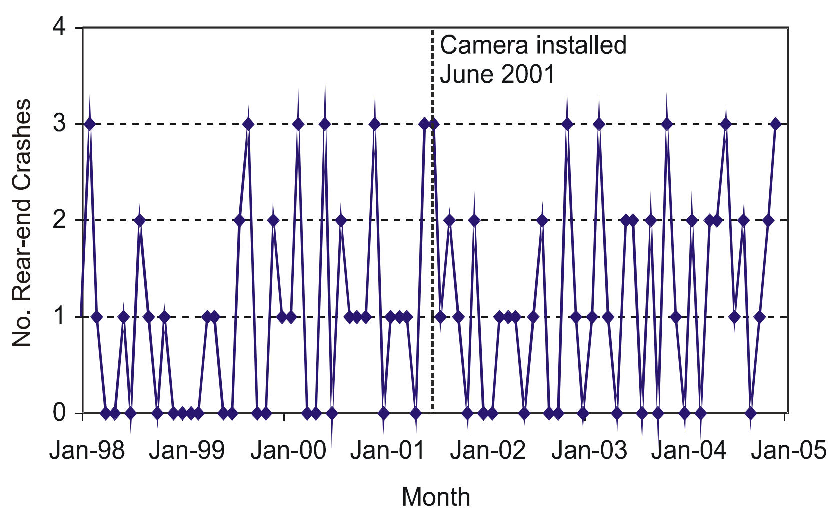

Figure 1. Number of Rear-end Crashes at Leesburg Pike and Dranesville Road

Even if this random variation were eliminated, however, there could be an external factor other than installation of a camera that causes crashes to increase. (For example, the volume could double.) Accordingly, to determine how a camera is affecting rear-end crashes, the proportion of rear-end crashes to total crashes should be assessed.

Accordingly, aggregated data from Fairfax County—the jurisdiction with the most extensive program consisting of 13 intersections with red light cameras—were used. The data were aggregated by month relative to the installation of the camera. For example, the hypothetical raw data shown in Table 10 can be considered for just two intersections. The data are tabulated as shown in Table 11. For Fairfax County, this approach was followed (except that Fairfax County had 13 intersections rather than just 2).

The rear-end crash data were examined as a proportion of the total number of crashes (rear-end and angle) for each month, as given in Eq. 5.

Proportion of rear-end crashes = Rear-end crashes/Total crashes [Eq. 5]

Table 10. Rear-end Crashes for Two Intersections

Intersection	Camera Date	April 2003	May 2003	June 2003	July 2003	August 2003
A	May 2003	5	6	8	10	12
B	June 2003	1	2	3	4	5

Table 11. Aggregate Rear-end Crashes Based on Two Intersections

2 Months Before Camera	1 Month Before Camera	Month of Camera Installation	1 Month After Camera Installation	2 Months After Camera Installation
Insufficient data	7	9	12	15

8. The severity of any injury crashes that occur does not change after camera installation. To study the impact of red light cameras on injury severity further, the following analysis was conducted:

- The total number of injuries in each injury severity category (1, 2, 3, or 4) was calculated at each intersection.
- The number of injuries in each severity category was calculated at each intersection for crashes that occurred *before* camera installation.
- The number of injuries in each severity category was calculated at each intersection for crashes that occurred *after* camera installation.
- The *distribution* of injuries across the four injury types was compared before and after camera installation.

In addition, the type of safety restraints being used by the driver of the automobile(s) at the time of the crash was considered. The Virginia FR 300 police report classifies safety restraints (also referred to as safety equipment) as *No restraint used, Lap belt, Harness, Lap belt and harness, Child restraint, Air bag,* and *Other*. For this analysis, for a driver to have been considered to be using proper safety restraints, the driver must have been classified as using a lap belt, harness, or lap belt and harness. The four calculations of injury analysis were conducted for drivers considered to have been using safety restraints and a third time for drivers not using proper safety restraints. This analysis does not determine whether the number of injury crashes changed; rather, it determines whether the severity of injury crashes changed relative to the total number of injury crashes.

RESULTS AND DISCUSSION

Overview of the Before-After Data

Tables B1 through B11 of Appendix B present the number of crashes for each crash type before and after the implementation of the cameras at each intersection, with the results normalized by time (e.g., crashes per intersection-year). Table B12 shows the aggregate number of crashes per intersection-year for each jurisdiction. Table B12 also shows that when all crashes are aggregated across all jurisdictions, it is clear that rear-end crashes increase overall (37%) and red light running crashes and injury red light running crashes decrease overall (29% and 30%, respectively, on an intersection-year basis). Results for the other three crash types indicate that total crashes increased by 23%, angle crashes increased by 4%, and injury crashes increased by 17% per intersection-year.

Yet Table B12 also shows that the results are not identical across jurisdictions. On an intersection-year basis, red light running crashes increased in Arlington by almost 40% and decreased in Vienna by more than 90%. Rear-end crashes increased in Fairfax County by 45% but by only 8% in Falls Church (and in Vienna, they *decreased* by 11%). Further, some crash types are more common than others; e.g., there are 2.78 rear-end crashes for every red light running crash per intersection-year during the before period. The increase in the former and the reduction in the latter means that the ratio climbs to more than 5.39 during the after period.

Tables C1 through C11 of Appendix C show similar results for the number of crashes per intersection-year normalized by traffic volume (e.g., crashes per intersection year divided by total ADT). Table C12 shows aggregate results similar to those in Table B12: an increase in rear-end crash rates (27%) and a decrease in both red light running crash rates (42%) and injury red light running crash rates (28%). Less dramatic changes were noted in the other three crash types: angle crash rates decreased by 6%, injury crash rates increased by 10%, and total crash rates increased by 12%. As was the case with Appendix B, there is substantial variation among jurisdictions: Vienna saw its injury crash rate drop by 17% whereas Fairfax City saw its injury crash rate increase by 7%.

Interpreting Tests of Statistical Significance

Two of the tests that follow—the paired *t*-tests and the GLMs—can be described as null hypothesis significance testing. In such tests, it is determined whether the data enable one to reject the hypothesis that the cameras had no effect on a particular crash type. In this report, if the *p*-value for such hypothesis testing is equal to or less than 0.05, then the hypothesis is rejected and one can infer that the cameras are correlated with a statistically significant increase (or decrease) in the crash type in question. (Although a *p*-value was not computed for the EB models, an equivalent technique is to determine whether the upper and lower bound of the estimated impact includes one, and if it does not, the impact is statistically significant. In this sense, the use of the EB approach may also be described as null hypothesis significance testing). Thus, when an increase or decrease is observed and the change is statistically significant, this change is reported as a significant increase or decrease.

When an increase or decrease is computed and is not found to be statistically significant, the question arises as to whether one should report (1) that "no significant change was found" or (2) that a "nonsignificant increase" or "nonsignificant decrease" was found. Certainly, full results with *p*-values (or confidence intervals) are presented in Appendices D through H. However, it is debatable as to which option is preferable when summarizing results: the phrase "nonsignificant increase" conveys all information but risks suggesting an increase that may truly be attributable to chance; the phrase "no significant change" carries no such risk but hides some (albeit imperfect) information about the result.

It is tempting, both for the sake of simplicity and for the comfort of using techniques as is commonly practiced, to follow the second option. However, examination of one article suggests that the first option is preferable in this report. Specifically, Hauer (2004) strongly argues that it is *incorrect* to assume that because the results of null hypothesis significance testing do not show statistical significance, the interpretation should be that a treatment had no effect. In particular, he singled out a 1976 study, conducted by a consultant for the Virginia Department of Highways and Transportation, and the accompanying transmittal letter written by the VDH&T Commissioner, as an illustration of how the lack of a statistically significant result is not the same as no effect. Upon examination of the before-after data presented in the consultant's report that examined the impact of allowing right-turn-on-red (RTOR), Hauer wrote:

> persons without training in statistics would think that after RTOR was allowed, these intersections were somewhat less safe. However, the consultant concluded, quite correctly, that the change was not statistically significant. The Commissioner of the Virginia Department of Highways and Transportation sent the consultant's report to the Governor and in the letter of transmittal wrote: "we can discern no significant hazard to motorists or pedestrians from implementation of the general permissive rule (i.e. of RTOR). No significant increase in traffic crashes has been noted following adoption of right-turn-on-red in any state including Virginia." Obviously, there was miscommunication. In English, 'significant' means 'having or likely to have considerable influence or effect'; the synonym of 'significant' is 'important'. In statistics 'not significant' means that the data is insufficient to reject the (null) hypothesis of 'no effect'. Thus, the consultant said one thing and the Commissioner transmitted something entirely different (Hauer, 2004, p. 495).

Hauer gave several examples of later reports showing increases in crashes following the allowance of RTOR where the authors continued to find an increase, which was not significant, and based on this finding concluded that RTOR did not impact the increase. Hauer (2004) noted that the problem continued until large datasets on RTOR were available. Thus, Hauer concluded, the "absence of statistical significance does not mean and should never be taken to mean that 0 is the most likely estimate" (Hauer, 2004, p. 497).

There is reason to suspect that this report could repeat the same mistake identified by Hauer if only statistically significant results were reported. This suspicion arises because of the relatively small numbers of sites and crashes in some jurisdictions. Some jurisdictions had a small number of sites where a camera was placed (e.g., Vienna had only three). Some jurisdictions had a small number of crashes of a particular type (e.g., there were only 22 red light running injury crashes in Falls Church during the entire study period). Thus, it is quite conceivable that the small datasets might lead to nonsignificant results but that when all of results were examined simultaneously, a clear pattern might emerge. Yet if only significant results were reported, any such patterns would be hidden.

The report also provides the results of each jurisdiction separately rather than in the aggregate. Certainly, this decision suffers from the disadvantage that not all jurisdictions had the same number of camera sites: Fairfax County had 13, Vienna had 3, and Alexandria only 1 (where before and after data could be collected). Thus, to some extent, it is plausible that differences in statistical levels are influenced by the different numbers of camera sites in each jurisdiction. However, aggregation of jurisdictions could mask important jurisdiction-specific findings—in fact, as will later be shown to be the case, in one jurisdiction, all crash types increased (sometimes significantly, sometimes not).

Given the two goals of (1) not losing information that might be hidden in patterns of nonsignificant changes and (2) not losing information pertaining to variation by jurisdiction, results of significance testing are presented in the following sections. Increases or decreases of any type are noted, and those with a *p*-value of 0.05 or less or, in the case of the EB approach, those where the confidence interval does not include 1.0) are prefixed with the adjective "significant." Those with a *p*-value greater than 0.05 (or, in the case of the EB approach, with a confidence interval that does include 1.0) are prefixed with the adjective "nonsignificant", which carries the same meaning as the adjective "insignificant" or "nonsignificant" that is found in other reports and articles. Full results are given in Appendices D and E (for the paired *t*-test normalized by time alone and normalized by time and traffic volume, respectively), Appendix F (for ANOVA), Appendix G (for GLM), and Appendix H (for the EB approach).

Associated Impacts of Cameras on Crash Frequency

Results Using Paired *t*-Tests

The analyses of the paired *t*-tests, normalized by time and by traffic volume (total ADT) did not consider the influence of confounding factors, but they are the easiest of the analyses to interpret. Details of the *t*-tests are given in Appendices D and E. Based on the before and after comparison, the findings are as follows:

1. *The presence of the cameras is generally associated with an increase in the number of rear-end crashes at camera sites.* In Arlington and Fairfax City, the increase is statistically nonsignificant, but in Fairfax County (the jurisdiction with the largest number of camera sites) the increase is statistically significant. In Vienna, a

nonsignificant decrease was found. In Falls Church, the two *t*-test methods produced different results, but in both cases the change was statistically nonsignificant.

2. *The analysis shows no statistically significant change in the number of rear-end crashes at comparison sites.* Arlington, Fairfax County, and Falls Church showed a nonsignificant decrease, and Fairfax County showed a nonsignificant decrease when normalized by time and traffic volume. Fairfax City and Vienna showed a nonsignificant increase.

3. *The presence of cameras is generally associated with a decrease in the number of red light running at camera sites.* In Fairfax City, Falls Church and Vienna, the decrease was statistically nonsignificant, but for Fairfax County, the decrease was statistically significant when normalized by time and traffic volume. In Arlington, there was a statistically nonsignificant increase.

4. *The analysis showed no significant change in the number of red light running crashes at comparison sites.* Arlington and Fairfax City showed a nonsignificant increase, and Falls Church and Vienna showed a nonsignificant decrease. For Fairfax County, the two *t*-test methods produced different results, but in both cases the change was statistically nonsignificant.

5. *The presence of the cameras produces mixed results for the change in the number of angle crashes at camera sites.* Arlington and Vienna showed a nonsignificant increase. Fairfax City and Fairfax County showed a nonsignificant decrease when normalized by time and traffic volume but a nonsignificant increase when normalized by time alone. Falls Church showed a nonsignificant decrease.

6. *The analysis showed no significant change in the number of angle crashes at comparison sites.* However, all jurisdictions except Fairfax City showed a nonsignificant increase.

7. *The presence of cameras is associated with a significant decrease in the number of red light running injury crashes at camera sites in one jurisdiction with nonsignificant results in the other four jurisdictions.* Arlington showed an increase that was statistically nonsignificant when normalized by time but statistically significant when normalized by time and traffic volume. For Fairfax City, Falls Church, and Vienna, the decrease was statistically nonsignificant, and for Fairfax County the decrease was statistically significant.

8. *The analysis showed no significant change in the number of injury red light running at comparison sites.* Arlington showed a statistically nonsignificant increase, and the other jurisdictions showed a statistically nonsignificant decrease.

9. *The presence of the cameras showed no significant change for the number of injury crashes at camera sites.* In Vienna, there was a statistically nonsignificant decrease, but in Arlington and Fairfax County, there was a statistically nonsignificant increase.

For Fairfax City and Falls Church, the two *t*-test methods yielded statistically nonsignificant changes, with one method showing an increase and the other a decrease.

10. *The analysis indicated a general increase in the number of injury crashes at comparison sites.* Arlington and Fairfax County showed a statistically nonsignificant decrease (when normalized by time and traffic volume). Fairfax City and Vienna showed a statistically nonsignificant increase and Falls Church showed a statistically significant increase when normalized by time and traffic volume.

11. *The presence of cameras yielded no significant change for total crashes at camera sites.* Fairfax City had a statistically nonsignificant increase, and Falls Church had a statistically nonsignificant decrease. For Arlington and Fairfax County, the results showed an increase which was significant for one method but nonsignificant for the other method. Vienna showed a statistically nonsignificant increase when normalized by time but a statistically nonsignificant decrease when normalized by time and traffic volume.

12. *The analysis showed no significant change for the number of total crashes at comparison sites.* Fairfax City and Vienna showed a statistically nonsignificant increase, whereas Arlington, Fairfax County (when normalized by time and traffic volume), and Falls Church showed a statistically nonsignificant decrease.

13. *The analysis shows no significant change in the number of crashes at spillover sites.* Rear-end crashes, angle crashes, and injury red light running showed a statistically nonsignificant increase in both *t*-tests. Red light running crashes, injury crashes, and total crashes showed a statistically nonsignificant increase when normalized by time alone and a statistically nonsignificant decrease when normalized by time and traffic volume.

The paired *t*-tests addressed at best two confounding factors: time and ADT which comprise the basis of the rates in Appendix C. The ANOVA, GLM, and EB methods addressed the other confounding factors together with time and ADT.

Results Using Analysis of Variance

The purpose of ANOVA is to determine which variables influence crash frequency for each of the crash categories. The results for each crash type in each jurisdiction are given in Appendix F. For the first-level ANOVA, factors that corresponded to a *p*-value less than 0.100 were considered significant and are listed in the results tables. For the second-level ANOVA for Fairfax County and the ANOVA of the combined jurisdictions, factors that corresponded to a *p*-value less than 0.05 were considered significant, whereas a threshold of 0.10 was used for the smaller jurisdictions. The reason for this larger threshold of 0.10 is that attaining a small *p*-value was generally more difficult in the smaller jurisdictions because of their correspondingly smaller datasets. The results obtained are shown in Tables F1 through F11 in Appendix F.

The first-level ANOVA revealed that for nearly all crash types in all the jurisdictions, the site identifier variable was significant and was associated with a very low *p*-value (e.g., 0.01 or lower), as shown in Tables F1, F3, F5, F7, F9, and F10. This result confirmed the need for the second-level ANOVA in which the site identifier variable was replaced with geometric data. The results of the second-level ANOVA were highly variable between crash types and jurisdictions, as shown in Tables F2, F4, F6, F8, and F11. The influence of the number of left-turn lanes was significant for each crash type in multiple jurisdictions. It should also be noted that the influence of a T intersection, the interaction of total ADT and the number of left-turn lanes, and the interaction of total ADT and curb cuts were significant for each crash type in at least one jurisdiction.

Although the ANOVA results did not conclusively identify specific variables that influenced crash frequencies, the information they provided aided in understanding the role of confounding factors and the screening process (determining which variables should be used in the GLMs).

Results Using Generalized Linear Modeling

Appendix G provides the results of the GLM, in addition to listing the developed equations. The model for rear-end crashes in Fairfax County is an example of the models and is shown by the following equation:

$$\text{Rear-end crashes} = \exp(2.04 + 0.27 * \text{Camera} + 5.50 * \text{Number of left-turn lanes} - 0.78 * \text{Speed limit} - 0.49 * \text{logAADT} * \text{Number of left-turn lanes} + 0.07 * \text{logAADT} * \text{Speed limit} + 0.06 * \text{ITEDiff} * \text{Truck percentage})$$

Findings based on the GLMs are as follows. For Fairfax City, these results are based on the use of major ADT and Adjustment Technique B. For the other jurisdictions, they are based on total ADT. The rationale for treating Fairfax City uniquely is discussed in the results of the sensitivity analysis.

1. *The cameras were generally associated with a significant increase in rear-end crashes.* This increase was statistically significant for Arlington ($p = 0.00$) and Fairfax County ($p = 0.05$). Falls Church, however, showed a statistically nonsignificant ($p = 0.29$) decrease. In Vienna, the combined main effect ($p = 0.00$) and interaction effect (camera and the number of left-turn lanes, $p = 0.00$) was associated with an increase in rear-end crashes with the presence of none or only one left-turn lane (17% of the cases); otherwise (87% of the cases), the cameras were associated with a decrease. In Fairfax City, the combined camera main effect ($p = 0.00$) and interaction effect (camera and presence of curb cuts, $p = 0.00$) showed the cameras to be associated with an increase in rear-end crashes. The results for Fairfax City (using major ADT and Adjustment Technique B) and the other jurisdictions (using total ADT) are provided in Tables G7 and G1 of Appendix G, respectively.

2. *The cameras were not associated with the same impact on red light running crashes in all jurisdictions*. In Fairfax City, the cameras were correlated with a statistically

significant decrease in red light running crashes ($p = 0.00$); the opposite was the case in Arlington (a significant increase with $p = 0.01$). The effect of cameras in Fairfax County, Falls Church, and Vienna was a statistically nonsignificant decrease ($p = 0.09$, $p = 0.21$ and $p = 0.47$, respectively). The results for Fairfax City (using major ADT and Adjustment Technique B) and the other jurisdictions (using total ADT) are provided in Tables G7 and G2 of Appendix G, respectively.

3. *The cameras were not associated with the same impact on angle crashes in all jurisdictions.* In Arlington and Vienna, the cameras were correlated with a statistically significant increase in angle crashes ($p = 0.00$ for both cases). The effect in Fairfax County ($p = 0.17$) and Fairfax City ($p = 0.35$) was a nonsignificant increase. In Falls Church, the effect was a statistically significant decrease ($p = 0.04$). The results for Fairfax City (using major ADT and Adjustment Technique B) and the other jurisdictions (using total ADT) are provided in Tables G7 and G3 of Appendix G, respectively.

4. *The cameras were not associated with the same impact on injury red light running crashes in all jurisdictions*. In Fairfax County ($p = 0.08$), Falls Church ($p = 0.38$), and Vienna ($p = 0.67$), the cameras were associated with a statistically nonsignificant decrease. In Fairfax City, the combination of the camera main effect (significant decrease with $p = 0.00$) and interaction effect (between camera and truck percentage, significant increase with $p = 0.01$) indicated a decrease in 60% of the cases (truck percentage less than or equal to 4) and an increase in 40% of the cases (truck percentage greater than 4). In Arlington, however, the cameras were associated with a significant increase in injury red light running crashes. The results for Fairfax City (using major ADT and Adjustment Technique B) and the other jurisdictions (using total ADT) are provided in Tables G7 and G4 of Appendix G, respectively.

5. *The cameras were generally associated with an increase in the total injury crashes in all jurisdictions*. In Arlington, Fairfax County and Vienna, the increase was statistically significant (p = 0.00, 0.04, and 0.04, respectively). In Falls Church, the increase was not statistically nonsignificant ($p = 0.08$). In Fairfax City, however, the combination of the camera main effect (significant decrease with $p = 0.05$) and interaction effect (between camera and truck percentage, significant increase with $p = 0.08$) indicated a decrease in 60% of the cases (truck percentage less than or equal to 4) and an increase in 40% of the cases (truck percentage greater than 4). The results for Fairfax City (using major ADT and Adjustment Technique B) and the other jurisdictions (using total ADT) are provided in Tables G7 and G5 of Appendix G, respectively.

6. *The cameras were not associated with the same impact on total crashes in all jurisdictions*. In Arlington and Fairfax County, there was a statistically significant increase in total crashes (p = 0.00 and 0.02, respectively). In Falls Church, the associated effect was the opposite: a statistically significant decrease. In Vienna, the associated effect was a nonsignificant increase ($p = 0.08$). In Fairfax City, the combination of the camera's main effect (significant increase with $p = 0.00$) and the

interaction effect (between camera and grade, significant decrease with $p = 0.00$) indicated an increase in total crashes. The results for Fairfax City (using Major ADT and Adjustment Technique B) and the other jurisdictions (using total ADT) are provided in Tables G7 and G6 of Appendix G, respectively.

The results indicate that the red light cameras were not associated with the same impact in all jurisdictions. This was most evident in Arlington County, where all crash types increased; in the other jurisdictions, some crash types increased and some decreased.

The cameras were associated with an increase in rear-end crashes in all jurisdictions except Falls Church, where they were correlated with a nonsignificant decrease in rear-end crashes. Decreases (some significant, some nonsignificant) in red light running crashes and injury red light running crashes were correlated with the cameras in all jurisdictions except Arlington. Finally, the cameras were associated with an increase in total injury crashes in all jurisdictions except Fairfax City.

One interaction effect should be noted: in Fairfax City where there were no curb cuts, the camera was associated with a substantive increase in rear-end crashes (with the coefficient for the main effect being 0.95). Where there was one or more curb cuts, the coefficient for the interaction effect was –0.93, such that the net associated impact of cameras was still an increase in rear-end crashes; however, the increase was slight as the sum of the two coefficients (0.95 and –0.93) is very close to 0.

Results Using Empirical Bayes Analysis

As shown in Appendix H, the EB results lead to the following findings as they relate to the six specific crash types and the comparison of the associated impacts of cameras across jurisdictions.

- *The cameras were associated with an increase in rear-end crashes*. Four of the five jurisdictions (Arlington, Fairfax County, Falls Church, and Vienna) listed in Table H1 of Appendix H showed a statistically significant increase. The exception was Fairfax City, where the analysis suggests that an increase may have occurred, although not statistically significant. The magnitude of this increase varied greatly by jurisdiction; however, the point estimate for Fairfax City was a 10% increase whereas the point estimate for Arlington County was a 139% increase.

- *The cameras were associated with a decrease in red light running crashes*. As shown in Table H2, the findings for two of the five jurisdictions directly support this finding with statistically significant decreases: Fairfax City and Fairfax County; further, Vienna had a nonsignificant decrease. The exceptions were Arlington County (with a significant increase) and Falls Church (with a nonsignificant increase).

- *The cameras were associated with an increase in angle crashes in two jurisdictions and a decrease in angle crashes in three jurisdictions.* As shown in Table H3, a statistically significant increase in angle crashes occurred in Arlington and a statistically nonsignificant increase occurred in Fairfax County. In contrast, Fairfax City showed a statistically significant decrease, and Falls Church and Vienna showed a nonsignificant decrease in angle crashes.

- *The cameras were associated with a decrease in injury red light running crashes in three jurisdictions.* As shown in Table H4, two of the five jurisdictions saw a significant decrease (Fairfax City and Vienna) and one (Fairfax County) saw a nonsignificant decrease. However, Falls Church and Arlington saw a nonsignificant increase, and when all results were combined, the point estimate was a nonsignificant increase. The small set of relatively few injury red light running crashes prevent conclusive results. For example, confidence intervals cannot be computed for Vienna because there were no injury red light running crashes during the after period.

- *In terms of total injury crashes, the cameras were correlated with a statistically significant increase in one jurisdiction (Arlington), a nonsignificant increase in two (Falls Church and Vienna), and a nonsignificant decrease in one (Fairfax City).* In Fairfax County, the change was nonsignificant and was either a slight increase or a slight decrease depending on whether a larger number of sites (with major road ADTs only) or a smaller number of sites (with both major and minor road ADTs) were used.

- *The cameras were associated with an increase in total crashes in four of five jurisdictions, as shown in Table H6.* A statistically significant increase occurred in two of the five jurisdictions (Arlington and Fairfax County) and a statistically nonsignificant increase occurred in Falls Church and Vienna. The exception was Fairfax City, which showed a nonsignificant decrease.

Clearly, however, an equally powerful result is that the associated impact of cameras on crash types was not uniform. Two jurisdictions in particular deviated from the norm: Arlington County and Fairfax City.

Unlike the other jurisdictions, Arlington County showed increases in all crash types, five of them significant. Neither data quality nor the analytical results explain this divergence. For example, although Arlington County had a small number of sites (just six), so did several other jurisdictions (Falls Church and Vienna had six, and Fairfax City had eight). Further, total volumes from the major and minor approaches were available for all six intersections in Arlington. Finally, Arlington's dispersion parameter (k) and maximum likelihood values were not outside the norm for the other jurisdictions. This suggests that particular site characteristics that are not yet known may have confounded these results.

Unlike the other jurisdictions, Fairfax City's point estimate for total injury crashes decreased rather than increased, as was the case with its total crashes. Further, with regard to the upper bound of the empirical confidence intervals, Fairfax City had arguably the greatest drop in injury red light running crashes and red light running crashes overall. Finally, although Fairfax City's rear-end crashes increased, the increase was nonsignificant; the increase was significant for all other jurisdictions.

It is tempting to report simply the aggregate results of combining data from all jurisdictions into a single dataset. Although this was done in this report, as shown in Tables H1 through H6 in Appendix H, this single number does not necessarily explain safety performance throughout the region because of the wide variation by intersection and by jurisdiction. For example, when the 6 Arlington sites, the 46 Fairfax County sites, the 8 Fairfax City sites, the 6 Falls Church sites, and the 6 Vienna sites (all based on major ADT) are combined into a single dataset for analyzing the impact of these cameras on rear-end crashes, the EB method suggests that rear-end crashes increase with a confidence interval of 31% to 54% as shown at the bottom of Table H1. However, this range does not explain the large increases estimated for Arlington (139%) and Falls Church (136%) or the small increases estimated for Fairfax City (10%) or Vienna (30%). In short, this confidence interval for all five jurisdictions combined does not include the point estimates for four of the five jurisdictions when each jurisdiction is estimated separately.

Summary of Impacts Based on the Three Major Statistical Tests

Table 12 summarizes the impacts of the three major categories of statistical tests used to assess the associated impacts of the cameras on the various crash types: the paired *t*-test, GLM, and EB analysis. ANOVA was not included because its findings were used to determine which confounding factors should receive further scrutiny in the more detailed GLM application. For the individual jurisdiction results, with five jurisdictions and six crash types, there are 30 possible cells where a conflict could exist among the three statistical tests. Table 12 indicates there were no *major* conflicts where one statistical test showed a significant increase and another showed a significant decrease.

Nine of the 30 cells show a *moderate* conflict: one test shows an increase and the other a decrease, with both or one nonsignificant. Such conflicts are not surprising for three reasons. First, the datasets varied by test. For example, the paired *t*-test used total volumes, which in Fairfax City were available for only six sites. For the EB and GLM approaches, six sites appear to give spurious results given that there are easily that many independent variables in the model; thus, eight sites were used where only the major ADT was used. Second, some tests address confounding factors whereas others do not: e.g., the paired *t*-test does not address changes in truck percentages that are addressed by the EB approach and GLM. Third, some tests account for the presence of interaction effects and others do not. For example, the GLM and ANOVA approaches consider the presence of two-way interaction effects and the EB approach and *t*-tests do not explicitly consider them. (The presence of interaction effects did not usually result in a discrepancy between the GLM and EB analysis results: e.g., in the case of Fairfax City rear-end crashes, Fairfax City injury red light running crashes, and Fairfax City total injury crashes, the GLM and EB results agree despite the presence of camera interaction effects in the GLM model.)

- *The two easiest cases to explain are the Falls Church injury red light running crashes and the Vienna rear-end crashes.* Injury red light running crashes are relatively few in number compared to the other crash types studied, and for some jurisdictions with only six sites, the number of injury red light running crashes is even fewer still. For example, in Falls Church (a jurisdiction with six sites total), there were just 22 such crashes during the entire 7-year study period. Thus it is plausible that spurious results

Table 12. Summary of Impacts Based on the Three Major Statistical Tests[a]

Jurisdiction	Test	Rear-end Crashes	Red Light Running Crashes	Angle Crashes	Red Light Running Injury Crashes	Injury Crashes	Total Crashes
Arlington	Paired *t*-test[b]	↑	↑	↑	↑	↑	⇧↑
	General Linear Models[c]	⇧	⇧	⇧	⇧	⇧	⇧
	Empirical Bayes[c]	⇧	⇧	⇧	↑	⇧	⇧
Fairfax City	Paired *t*-test[b]	↑	↓	↑↓	↓	↓↑	↑
	General Linear Models[c]	↑[d]	⇩	↑	↓[d]	↓[d]	↑[d]
	Empirical Bayes[c]	↑-	⇩	⇩	⇩	↓-	↓
Fairfax County	Paired *t*-test[b]	⇧	⇩	↓	⇩	↑	⇧↑
	General Linear Models[c]	⇧	↓	↑	↓	⇧	⇧
	Empirical Bayes[c]	⇧	⇩	↑-	↓	↑-	⇧
Falls Church	Paired *t*-test[b]	↑↓	↓	↓	↓	↑↓	↓
	General Linear Models[c]	↓	↓	⇩	↓	↑	⇩
	Empirical Bayes[c]	⇧	↑	↓	↑	↑	↑
Vienna	Paired *t*-test[b]	↓	↓	↑	↓	↓	↑↓
	General Linear Models[c]	↓[d]	↓	⇧	↓	⇧	↑
	Empirical Bayes[c]	⇧	↓	↓-	⇩	⇧	↑
All Jurisdictions Combined	Empirical Bayes	⇧	↓	⇧	↑	⇧	⇧

[a]Significant decrease (⇩), nonsignificant decrease (↓); nonsignificant increase (↑); significant increase (⇧); see Appendix H because the confidence interval is very nearly centered around one (-).
[b] When the two paired *t*-test methods gave different answers, both answers are shown; the left is based on Appendix D (normalized by time only) and the right is based on Appendix E (normalized by time and traffic volume).
[c] Datasets varied slightly for these tests because the optimal dataset for each test was used. For example, for the paired *t*-test, it was better to use fewer sites (with total ADT at each site) but for the EB approach, it was better to use more sites (even though at such sites only the major ADT rather than the total ADT was available). For GLM, total ADT was used for all jurisdictions except Fairfax City, where major ADT is reported. (For Fairfax City, results based on Adjustment Technique B and the major ADT are reported.)
[d]The GLMs also had a second-order interaction effect between camera and another independent variable. The combination of camera main effect and interaction effect can cause an increase or a decrease depending on the value of the interacting variable. The arrow indicates the direction of change in the majority of cases; the statistical significance of the main or interaction effect is not represented here but is shown in Tables G7 and G8.

could be obtained with such a small number. The discrepant rear-end crash results for Vienna appear to be due to confounding factors and interaction effects: the results of the paired *t*-tests and GLM (which showed a nonsignificant decrease) are likely different from those of the EB approach (which showed a significant increase) because GLM accounts for both confounding factors and interaction effects, the EB approach accounts only for confounding factors and the paired *t*-test accounts for neither.

- *Four more cases are not quite so easily explained but appear resolvable.* Fairfax County angle crashes, Vienna angle crashes, and Vienna injury crashes clearly involve impacts other than the cameras. (For example, *injury crashes* is a broad category that includes run-off-the-road crashes, which presumably should not be affected by the cameras. Thus, it appears plausible that statistically significant results could not be discerned for these three crash categories; this conclusion is consistent with the findings in other jurisdictions, which generally showed mixed results.) The two exceptions are Arlington (where generally all crash types increased) and Fairfax City (where angle crashes increased, but the dataset was small). Falls Church red light running crash results may be attributed to a small dataset, given that none of the changes was significant.

- *The conflict for Falls Church rear-end crashes is challenging: one paired t-test method showed a nonsignificant increase and the other a nonsignificant decrease, the GLM showed a nonsignificant decrease, and the EB showed a significant increase.* Although it does seem plausible to presume that rear-end crashes are increasing simply because they increase in every other jurisdiction, the fact that the GLM suggested a nonsignificant decrease is difficult to explain in the context of the other results.

- *The cases of Fairfax City total crashes and Vienna rear-end crashes may be due to the presence of interaction effects.* The GLM results are in conflict with the EB results and agree with the paired *t*-tests. In both cases, the GLM included a camera interaction effect with another variable. It is plausible that since the EB approach does not explicitly account for interaction effects and considers only a fixed set of independent variables, the different results may be attributed to differences in the models.

- *The most difficult moderate conflict to explain is the impact on total crashes in Falls Church.* Because rear-end crashes are a common type of crash, it is plausible that the results for total crashes should mirror those for rear-end crashes; this concept is valid for the EB and GLM tests but not for the paired *t*-test. More germane, however, is the fact that unlike rear-end crashes and red light running crashes, total crashes were not affected by cameras in a similar manner across all jurisdictions. For this reason, the true impact of cameras on crash types in Falls Church is difficult to discern from the EB method alone.

There are also two conflicts that relate to the summary of results across all jurisdictions, and both appear to be easily resolvable. The first conflict is that a simple comparison of before-after crash rates by intersection suggests a 6% drop in angle crash rates (Table C12 in Appendix C) whereas the EB estimate suggests a 20% increase (Table H3 in Appendix H). The difference in this case is probably due to the EB estimate accounting for confounding factors and not assuming a proportionate impact of volume on crash risk (e.g., the EB approach does not assume that a doubling of traffic volume will double the crash risk but rather provides an estimate based on the observed data). Given that both the EB and the GLM analyses suggested a nonsignificant increase in angle crashes in the largest jurisdiction (Fairfax County), the EB aggregate result is probably accurate.

The second conflict is that the EB result suggests a 7% increase in injury red light running crashes (Table H4) but a before-after comparison suggests a 28% decrease (Table C12). Unlike the previous conflict, the EB range includes one—i.e., the increase (according to the EB method) is not statistically significant. It is probably the case that the average increase of 7% is due to the large increases suggested in Arlington and Falls Church. A potential contributing factor is the large number of injury *rear-end* crashes coded as red light running crashes. However, there were a total of 204 injury red light running crashes at camera intersections as shown in Appendix D, and only 11 of these were rear-end crashes (with 2 of these 11 being coded as rear-end crashes for one vehicle and angle crashes for the other vehicle); thus, this potential contributing factor does not appear to explain this discrepancy. Further, all tests in most jurisdictions (except Arlington) indicated decreased red light running crashes. The EB results also suggested that injury red light running crashes decreased (significant decreases in two jurisdictions, a nonsignificant decrease in a third jurisdiction) except in Arlington and Falls Church, where there was a nonsignificant increase. Given these findings and given that there was no indication that the number of red light running injury crashes should move in a different direction than red light running crashes, it seems that the correct inference is that cameras are associated with a decrease in red light running injury crashes and that the positive value of 7% is due to chance.

Associated Impacts of Cameras on Net Injury Severity

Table B12 in Appendix B showed that injury crashes across all intersections increased by about 17% per intersection-year after the installation of the cameras. However, not all crash types are necessarily equally severe. Because particular crash types increased and others decreased, one way to evaluate the net safety impacts of the cameras is to use average comprehensive crash costs for each crash. These comprehensive crash costs include not just vehicular damage but also medical and other costs based on national characteristics such as speed limit and crash type. Table 13 summarizes the comprehensive crash cost analysis for all six jurisdictions. The results are shown for two methodologies used in the calculation: crashes normalized by time (per intersection-year) and by traffic volume (by major ADT). The results are based on monetization of rear-end and angle crashes, which generally accounted for most (88%) of the crashes at an intersection. As explained in Table ES5, the cameras are probably responsible for *part* of the increase in rear-end crashes (because some rear-end crashes may result from camera installation) and *part* of the decrease in red light running crashes (because although almost all red light running crashes are angle crashes, some angle crashes are not red light running crashes). The comparison of rear-end and angle crashes is an imperfect attempt to capture the impact of the cameras on rear-end crashes attributable to the cameras and angle crashes attributable to the cameras.

The values in Columns 3, 4, and 5 of Table 13 rely solely on whether a crash was an injury crash or a non-injury crash and do not require the officer's indication of crash severity. For example, Table 6 showed that FHWA indicates that the cost of an injury rear-end crash at an intersection with a speed limit of 45 mph or less is $44,120 if the injury severity is unknown

Table 13. Net Change in Comprehensive Crash Costs After Camera Installation[a]

Jurisdiction (1)	Results Normalized by (2)	Officer's Indication of Crash Severity Not Used: Crashes With Injury (3)	Officer's Indication of Crash Severity Not Used: Crashes Without Injury (4)	Officer's Indication of Crash Severity Not Used: All Crashes (5)	Officer's Indication of Crash Severity Used: [b]All Crashes Based on KABCO (best guess) (6)	Officer's Indication of Crash Severity Used: [c]All Crashes Based on KABCO (alternative) (7)
Alexandria	Time	224,902	–72,945	151,957	90,555	130,557
	ADT	16,812	–7,201	9,611	4,421	8,022
Arlington	Time	–257,267	–68,828	–326,095	–140,883	–317,420
	ADT	–11,419	–3,353	–14,772	–5,180	–15,666
Fairfax City	Time	142,957	–299,921	-156,964	31,956	–175,354
	ADT	8,676	–16,895	-8,219	10,258	–9,830
Fairfax County	Time	–538,219	–390,049	–928,268	–2,944,295	–3,240,056
	ADT	–13,786	–13,661	–27,447	–123,542	–149,082
Falls Church	Time	–67,771	44,036	–23,735	14,094	–17,087
	ADT	–4,252	4,659	407	3,845	918
Vienna	Time	94,796	–19,038	75,758	92,367	57,342
	ADT	9,748	–944	8,804	10,140	7,270
All Jurisdictions	Time	–400,602	–806,745	–1,207,347	–2,856,206	–3,562,018
	ADT	5,779	–37,395	–31,616	–100,058	–158,368

[a]Dollar amounts represent the safety impact assuming costs for various crash severities for changes in angle and rear-end crashes following the installation of the camera. A positive amount suggests the cameras were associated with a positive safety impact, and a negative amount suggests the cameras were associated with a negative safety impact.
[b]Links KABCO and Virginia severities as follows: 1 = K, 2 = A, 3 = B, and 4 = C.
[c]Links KABCO and Virginia severities as follows: 1 = K, 2 = B, 3 = B, and 4 = C.

(Council et al., 2005). This means that whether a rear-end crash injury resulted in a minor or life-threatening injury, the same cost ($44,120) is applied to each injury rear-end crash. Thus, in Table 13, for Alexandria, monetization of the increased rear-end crashes and the decreased angle crashes suggests that the cameras were associated with a positive safety impact of $224,902 per year when only injury crashes were considered. Yet, the cameras were associated with a negative safety impact of $72,945 per year when only non-injury crashes were considered. Summing these two results suggests that the cameras were associated with an annual net safety benefit of $151,957 for Alexandria. Detailed information on how the comprehensive crash cost analysis was performed is provided in Appendix I.

Columns 6 and 7 of Table 13 show the results obtained if the officer's severity rating (1, 2, 3, 4) for injury crashes is linked to the KABCO severity rating. Under KABCO, FHWA assigns a specific dollar amount to each level of injury (Council et al., 2005). For example, the cost of a rear-end crash resulting in a disabling injury (Injury Level A) for speed limits less than 45 mph is $84,820, as described in Table 7. Thus, Virginia rear-end crashes where the officer assigned an injury rating of 2 at the scene of the crash are presumed to have a KABCO injury level of A. Based on these officer severity ratings, the investigators' best guess for linking these two scales suggests that the cameras in Alexandria were associated with an overall safety benefit of $90,555 per year. Further, even if the alternative method is used, the associated safety benefit is higher: $130,557 per year.

Table 13 shows three relevant findings if the officer's indication of severity at the scene of the crash is *not* used.

1. *When only injury crashes were considered* (such that all injury crashes are weighted equally), the cameras were associated with a positive safety impact in three jurisdictions (Alexandria, Fairfax City, and Vienna) and a negative safety impact in three jurisdictions (Arlington, Fairfax County, and Falls Church). When all intersections are aggregated, the cameras were associated with a positive safety impact on injury crashes when normalized by ADT but a negative safety impact when normalized by time.

2. *When only non-injury crashes were considered*, the cameras were associated with a negative impact in all jurisdictions except Falls Church.

3. *When all crashes (injury and non-injury) were combined,* the cameras were associated with a positive safety impact in two jurisdictions (Alexandria and Vienna), a negative safety impact in three jurisdictions (Arlington, Fairfax City, and Fairfax County), and varying safety impacts that depend on the method of normalization in one jurisdiction (Falls Church). In the aggregate for all jurisdictions, a net negative safety impact was found.

Table 13 also shows the results obtained if the officer's indication of severity *is* used. Using the method given in this report for linking KABCO and the officer's indication of severity, net positive safety benefits were indicated in four jurisdictions (Alexandria, Fairfax City, Falls Church, and Vienna) and net negative safety benefits were indicated in Fairfax County and Arlington. The alternative method of linking the KABCO and Virginia scales suggested similar results with Falls Church (when results are normalized by time) and Fairfax City, changing signs from a positive to a negative benefit.

Yet despite the fact that more jurisdictions showed a positive benefit when the officer's indication of severity was used, combining all intersections suggested a net *negative* benefit. The reason for this discrepancy is illustrated with Table 14. The large negative result for Fairfax County is causing the discrepancy, and the reason for Fairfax's negative number is the three fatal crashes that occurred therein during the camera after period. The cost of each fatal crash exceeds $4 million as shown in Table 6—about 40 times the cost of the most severe nonfatal injury (type A) crash. This explains why the negative safety impact of the cameras when all jurisdictions were aggregated was so much worse in the right side of Table 13 (e.g., a comprehensive crash cost *increase* of $100,058 assuming 1 million entering vehicles at each intersection) than the left side (e.g., a comprehensive crash cost *decrease* of $5,779 assuming 1 million entering vehicles at each intersection). This discrepancy is largely due to the three fatal crashes in Fairfax County—the only fatal crashes that occurred during this study—which had a combined cost of $2,562,784.

Because there were so few fatal crashes (3 of a total of 1,168 injury crashes used in this portion of the analysis), caution should be exercised when basing judgments on the impact of the small number of fatal crashes alone. The difference between a fatal crash and an injury crash may, for example, be attributed to the occupant's health prior to the crash, the use of safety restraints, the crashworthiness of the vehicle, or the occupant's position in the vehicle, in addition to the impact of the camera. For these reasons, it is generally more productive to focus on injury crashes in addition to fatal crashes. If the three fatal crashes in Fairfax were removed from Table 14, injury crashes for all jurisdictions combined would simply be the sum of the A, B, and C costs shown at the bottom of the table: $1,137,230 – $11,284 – $612,622 = $513,324. This positive sum, shown at the bottom of Table 15, would indicate that the cameras had an associated net safety benefit in terms of injury crashes when aggregated across all jurisdictions.

Table 15 thus presents the data from Table 14 with the three fatal Fairfax County crashes removed and splits the data into injury crashes only (A+B+C) and total crashes (A+B+C+O). Excluding fatal and non-injury crashes, the cameras were associated with a very small net positive safety impact in Fairfax County and more substantive positive safety impacts in Alexandria, Fairfax City, and Vienna, resulting in an aggregate positive safety impact for injury

Table 14. Net Change in Comprehensive Crash Costs Based on Officer's Indication of Crash Severity After Camera Installation[a]

Jurisdiction	Crashes With Injury				Crashes Without Injury	All Crashes
	K	A	B	C	O	Total
Alexandria	0	–74,698	40,666	197,532	–72,945	90,555
Arlington	0	301,395	17,083	–390,532	–68,828	–140,883
Fairfax City	0	368,587	–95,181	58,471	–299,921	31,956
Fairfax County	–2,562,784	434,330	93,342	–519,133	–390,049	–2,944,295
Falls Church	0	50,801	–11,235	–69,507	44,036	14,094
Vienna	0	56,815	–55,959	110,547	–19,038	92,367
Total	–2,562,784	1,137,230	–11,284	–612,622	–806,745	–2,856,206

[a]Links the KABCO and Virginia severity scales as follows: 1 = K, 2 = A, 3 = B, and 4 = C. Results normalized by time. A negative amount suggests the cameras are associated with a negative (bad) safety impact; e.g., in Alexandria, the cameras were associated with an increase in comprehensive crash costs of $74,698 for Type A injury crashes.

Table 15. Modified Net Change in Comprehensive Crash Cost After Camera Installation with Three Fatal Crashes Removed

Jurisdiction	Injury Crashes Only (A+B+C)	All Crashes (A+B+C+O)
Alexandria	163,500	90,555
Arlington	–72,054	–140,883
Fairfax City	331,877	31,956
Fairfax County[a]	8,539	–381,510
Falls Church	–29,941	14,094
Vienna	111,403	92,367
Total	513,324	–293,421

[a]Three fatal angle crashes that occurred in Fairfax County were removed from the analysis. Results normalized by time. A positive amount suggests the cameras were associated with a positive (good) safety impact; e.g., in Alexandria, the cameras were associated with a reduction in comprehensive crash costs of $163,500 for injury-only crashes.

crashes. Still, the negative safety impacts in Arlington and Falls Church (for injury crashes) is a reminder that the cameras were associated with net positive safety impacts in some jurisdictions and negative safety impacts in others, again in terms of injury crashes only.

The associated impact on injury crashes only in Table 15 (shown as *positive* \$513,324) can be contrasted with the impact on injury crashes only from Table 13 (shown as *negative* \$400,602). The results in Table 15 are based on the A, B, and C severity levels whereas the results in Table 13 assume the same cost for all injury crashes. Thus, the discrepant effects of cameras on injury crashes are attributed to whether or not the injury severities of A, B, and C are used.

Equally important, these results show that the cameras' associated impact on injuries was almost "too close to call." A total of 29 intersections comprised the analysis shown in Tables 13, 14, and 15. If all injury crashes are weighted equally—as they were in Table 13—the answer obtained by dividing the negative \$400,602 by 29 intersections suggests the cameras were associated with an increase in comprehensive crash costs of \$400,602/29 = \$13,814 per intersection-year. In contrast, if injury types A, B, and C are used—and if the three fatal crashes are omitted from the analysis as was done in Table 15—it can be said that the cameras were associated with a reduction in comprehensive crash costs of \$513,324/29 = \$17,701 per intersection-year. To place these figures in context, both of them (–\$13,814 or +\$17,701) are *less* than the comprehensive crash costs for a property-damage-only crash!

In summary, one might discount the three Fairfax County fatal crashes and thus argue that the cameras were associated with a more positive benefit, as shown in Table 15. However, one would also have to say that the accuracy of this position is dependent on using different severity levels and that a different finding would result if those severity levels were not used. With those caveats, Table 15 shows that the cameras were associated with a decrease in injury severity and an increase in property damage costs. Such an assessment is consistent with the belief that a reduction in red light running crashes would result in a reduction in crash severity (as such crashes are angle crashes that are typically relatively severe) and an increase in rear-end crashes (which are typically less severe). In addition, the results can vary by jurisdiction: The findings for Falls Church, which ran counter to these trends, cannot be ignored.

Sensitivity Tests of the Eight Assumptions Used in This Study

The results of the eight sets of sensitivity tests listed in Table 9 indicated the impact of the eight assumptions used in this report on the results. As was discussed previously, some of these assumptions pertained to the methodology (e.g., whether to use more sites with incomplete traffic volumes or fewer sites with complete traffic volumes) and some pertained to the availability of data (e.g., is it feasible to use Virginia-specific comprehensive crash costs instead of deriving these costs from national studies)?

Sensitivity Test 1: Major ADT vs. Total ADT (Paired *t*-test and ANOVA)

The use of major ADT as compared to the use of total ADT yielded few differences for the *t*-tests and ANOVA based on a detailed examination of the Fairfax City results. As shown in Table 16, there were no changes in statistical significance and only one change in direction: major ADT suggested a nonsignificant decrease in injury crashes and total ADT suggested a nonsignificant increase, but both had relatively large *p*-values (0.75 and 0.82, respectively).

The use of total versus major ADT also did not affect the ANOVA results substantially. In Fairfax City, there were six crash types and 11 significance impacts measured (based on the first-order impacts of five variables and the second-order impacts of four variables). Thus, there could have been 6 x 11 = 66 rows where a conflict arose (e.g.., use of major ADT rather than total ADT changed an effect from being significant to nonsignificant). Table 17, however, shows just eight such conflicts—e.g., in about 12% of the cases, there was a change from significant to nonsignificant or vice-versa. In the remaining 88% of the cases, there was no change.

Table 16. Sensitivity Tests of ADT in Fairfax City Paired *t*-Tests

Crash Type	Change Using Major ADT[a]	Change Using Total ADT[a]
Rear-end crashes	Nonsignificant increase (0.215)	Nonsignificant increase (0.161)
Red light running crashes	Nonsignificant decrease (0.313)	Nonsignificant decrease (0.431)
Angle crashes	Nonsignificant decrease (0.872)	Nonsignificant decrease (0.802)
Injury red light running crashes	Nonsignificant decrease (0.469)	Nonsignificant decrease (0.795)
Injury crashes	Nonsignificant decrease (0.750)	Nonsignificant increase (0.820)
Total crashes	Nonsignificant increase (0.557)	Nonsignificant increase (0.670)

[a]The *p*-values from the ANOVA are given in parentheses.

Table 17. Sensitivity Tests of ADT in Fairfax City ANOVA

Crash Type	Factor	Influence of Factor Using Total ADT[a]	Influence of Factor Using Major ADT[a]
Rear-end crashes	Site	Nonsignificant (0.913)	Significant (0.000)
	Truck Percent	Significant (0.048)	Nonsignificant (0.363)
Red light running crashes	No changes		
Angle crashes	Site	Nonsignificant (0.338)	Significant (0.038)
Red light running injury crashes	Total ADT	Significant (0.048)	Nonsignificant (0.914)
	Total ADT * Truck	Nonsignificant (0.590)	Significant (0.027)
Injury crashes	Site	Nonsignificant (0.595)	Significant (0.001)
Total crashes	Site	Nonsignificant (0.218)	Significant (0.000)
	Truck Percent	Significant (0.009)	Nonsignificant (0.373)

[a]The *p*-values from the ANOVA are given in parentheses.

Sensitivity Test 2: Major ADT vs. Total ADT (GLM and EB)

Table 18 shows the results of the GLMs for Fairfax City based on the camera's main effect. There are several striking differences: e.g., using the total ADT suggests that cameras were associated with a nonsignificant increase in red light running crashes and the use of major ADT suggests cameras were associated with a significant reduction in red light running crashes.

Table 18. Sensitivity Tests of ADT in GLM for Fairfax City[a]

Crash Type	Influence of Camera Using Total ADT (6 Sites used)	Influence of Camera Using Major ADT (8 sites used)
Red light running crashes	Significant increase (0.00)[b]	Significant decrease (0.00)
Injury red light running crashes	Significant decrease (0.00)[b]	Significant decrease (0.00)[b]
Rear-end crashes	Significant increase (0.00)[b]	Significant increase (0.00)[b]
Angle crashes	Significant decrease (0.00)[bb]	Nonsignificant increase (0.35)
Injury crashes	Significant decrease (0.00)[b]	Significant decrease (0.05)[b]
Total crashes	Significant increase (0.01)[b]	Significant increase (0.00)[b]

[a]Analysis based on Adjustment Technique B for the Fairfax City dataset. The Fairfax City cameras were installed in May 1998, which yielded only 4 months of before data (January-April) of that year. These 4 months of before data were converted to 1 year of before data and were used as the basis for crash estimation models for Fairfax City. For example, during these 4 months, there were 8 red light running crashes between January and April 1998. For the purposes of calibrating the crash estimation model, an annual crash rate of 24 red light running crashes for all of 1998 was assumed. Then, the crashes that occurred during the period May-December 1998 were also converted to an annualized figure, and these were considered as a full after year of the dataset. This method excludes the 2004 period from the after dataset.

[b]The GLM models revealed an interaction effect between camera and another independent variable, in addition to the camera main effect, which had a statistically significant impact on the occurrence of crashes.

Table 19 shows the results of the EB analysis for Fairfax City. As was the case in Table 18, the use of major ADT as opposed to total ADT caused some differences. Notably, the use of total ADT suggests that cameras were associated with a significant decrease in rear-end crashes whereas the use of major ADT suggests the cameras were associated with a nonsignificant increase in rear-end crashes.

It appears that the EB results and the GLM results were sensitive to the change from total ADT to major ADT because this change affected the number of sites—and Fairfax City has a relatively small dataset. Because there are just six sites that have a total ADT—and six independent variables in the crash estimation model—it *may* be the case that the small number of sites (six in the case of total ADT) yields spurious results for Fairfax City. By using eight sites (which is possible when only major ADT is used), there are at least more sites than there are independent variables in the EB crash estimation model. Thus, when there is a small number of sites (e.g., six or eight), it is better to use major ADT if that will allow a larger number of sites than would be allowed by total ADT.

Table 19. Sensitivity Tests of the Empirical Bayes Approach for Fairfax City[a]

Crash Type	Influence of Camera Using Total ADT (6 sites used)	Influence of Camera Using Major ADT (8 sites used)
Red light running crashes	Significant decrease (θ=0.24)	Significant decrease (θ=0.34)
Injury red light running crashes	Significant decrease (θ=0.04)	Significant decrease (θ=0.01)
Rear-end crashes	Significant decrease (θ=0.30)	Nonsignificant increase (θ=1.10)
Angle crashes	Significant decrease (θ=0.48)	Significant decrease (θ=0.68)
Injury crashes	Significant decrease (θ=0.14)	Nonsignificant decrease (θ=0.95)
Total crashes	Significant decrease (θ=0.22)	Nonsignificant decrease (θ=0.93)

[a]Analysis based on Adjustment Technique A for the Fairfax City dataset. The Fairfax City cameras were installed in May 1998, which yielded only 4 months of before data (January-April) of that year. These 4 months of before data were converted to 1 year of before data and were used as the basis for crash estimation models for Fairfax City. For example, during these 4 months, there were 8 red light running crashes between January and April 1998. For the purposes of calibrating the crash estimation model, an annual crash rate of 24 red light running crashes for all of 1998 was assumed. Thus, the crashes that occurred between May and December 1998 (e.g., the very first 8 months after the cameras were installed), were not included in this analysis.

Alternatively, a case could have been made for using total ADT (Adjustment Technique B) for Fairfax City based on the fact that the total impacts of the camera (i.e., main effect plus interaction effects) had relatively few conflicts with the EB method. This alternative has one advantage compared to the two advantages offered by the alternative selected in this study (major ADT, Adjustment Technique B, selected based on main effects of camera). The one advantage of using total ADT and Adjustment Technique B is simply that in the aggregate, the results match the results using the EB method. The first advantage of the alternative selected in this study (major ADT, Adjustment Technique B) is that since the EB approach does not explicitly include interaction effects, the camera main effects of the EB approach are thus consistent with the camera main effects of the GLM approach, meaning that any disparity between the GLM and EB results is likely due to the explanatory power of the explicit interaction effects (which are present only in the GLM). The second advantage of the alternative selected in this study (major ADT, Adjustment Technique B) is that as shown in Tables 18 and 19, the statistical significance of the main effect of the camera (as reported through the use of GLM and the EB approach) may be directly compared.

A comparison of Tables 18 and 19 shows that there are three major conflicts between the EB and GLM methods when total ADT (with six sites) was used: the GLM in Table 18 shows angle, total, and injury crashes to increase significantly whereas the EB method in Table 19 shows these crash types to decrease significantly. There was no major conflict (where one method shows a crash type to increase significantly and the other method shows the crash type to decrease significantly) when major ADT (with eight sites) was used.

When the number of sites was large (e.g., 40 sites with total ADT versus 46 sites with major ADT), this distinction is not critical. Indeed, Appendix H shows that results for Fairfax County (not Fairfax City) are almost identical regardless of whether total ADT or major ADT was used because each allows a large number of sites in the dataset.

Sensitivity Test 3: Adjustment Technique A and Adjustment Technique B for Fairfax City

As explained in the footnotes for Tables 18 and 19, there were two imperfect alternatives for analyzing Fairfax City results because of the very short period where cameras were not installed. Cameras were installed in May 1998, yielding just 4 months of before data. Thus, two approaches were considered for developing a crash estimation model: Adjustment Technique A, where the 4 months of before data were converted to an annual figure for 1998 (and thus the crash data for May–December 1998 were excluded from the analysis) and Adjustment Technique B (where the crash data for May–December 1998 were converted to an annual figure but then the 2004 crash data were excluded in order to use existing spreadsheet applications that had been customized for this analysis).

For the EB method in Fairfax City with major ADT, Adjustment Technique A and Adjustment Technique B yielded comparable results (e.g., cameras were associated with a rear-end crash increase of 10% using Adjustment Technique A [as shown in Table 19] and 14% using Adjustment Technique B). For all six crash types, the same direction (e.g., increase or decrease) and the same statistical finding (significant or nonsignificant) resulted. Thus, the right column of Table 19 is insensitive to the use of Adjustment Technique A or Adjustment Technique B. A direct comparison of these two approaches for the EB method is shown in Table H7 in Appendix H.

For the GLM method in Fairfax City with major ADT, Adjustment Technique A and Adjustment Technique B gave different results. For example, Adjustment Technique A suggested that cameras were associated with a significant decrease in rear-end crashes ($p = 0.02$) whereas Adjustment Technique B suggested that cameras were associated with a significant increase in rear-end crashes ($p = 0.00$ as shown in Table 18). Thus, the right column of Table 18 is affected by which approach is used. Considering that cameras in all other jurisdictions (and with the EB method in this jurisdiction) were shown to be associated with a significant increase in rear-end crashes, it would appear that the Adjustment Technique B given in Table 18 is more appropriate than Adjustment Technique A for the GLM. In fact, the EB method and the GLM method had no major conflicts for Fairfax City when the GLM method with major ADT and Adjustment Technique B was used. Thus, the results of Adjustment Technique B with major ADT were used in Table 18. A direct comparison of the GLM method (with Adjustment Technique A or Adjustment Technique B and with major ADT or total ADT) is shown in Tables G7 and G8 in Appendix G, and a comparison of these results with the EB method is given in Table H8 in Appendix H.

Sensitivity Test 4: Yellow Interval Change in Empirical Bayes

The EB approach classified the independent variables by year; e.g., an intersection was classified as having a major ADT of 46,800 in 1998 and a major ADT of 49,400 in 1999. Some variables, however, changed within 1 year, such as the duration of the yellow interval. To investigate the sensitivity, the investigators computed the index of effectiveness, its lower confidence limits, and its upper confidence limits in three scenarios for one particular crash type with an earlier version of the Fairfax County dataset as shown in Table 19.

1. rounding any change in signal timing to the beginning of the current year (e.g., a change in March 2003 is classified as January 2003)

2. rounding any change in signal timing as having occurred at the beginning of the following year (e.g., a change in March 2003 is classified as January 2004)

3. rounding any change in timing to the closest year (e.g., a change in March 2003 is classified as January 2003 but a change in October 2003 is classified as March 2004).

Table 20 shows that, as expected, the change in the yellow interval was associated with an impact for this crash type, but only by a few percentage points. The third scenario was followed for this analysis. Because the results did not change substantially, no further sensitivity tests were conducted.

Table 20. Sensitivity of Crash Reduction to Rounding Procedure for Signal Timing

Scenario	Index of Effectiveness θ	Lower Bound of θ	Upper Bound of θ
1	1.03	0.89	1.17
2	1.04	0.91	1.18
3	1.01	0.88	1.15

Sensitivity Test 5: KABCO and Virginia Injury Scales

In calculating comprehensive crash costs, the KABCO and Virginia injury scales had to be linked. As shown in Table 8, two methods of linking the scales were considered. As shown in Table 13, results were computed for the six individual jurisdictions plus the entire set of jurisdictions, and in each instance results were computed twice: once normalized by time and once normalized by ADT. Thus, there were 14 cases where the consistency of the two methods for linking the scales could be tested.

The results using the two methods were not consistent in three of the cases. In Fairfax City, whether normalized by time or ADT, the first method suggested cameras would be associated with a positive safety impact whereas the second method suggested the cameras would be associated with a negative safety impact. The results of the two methods were also not consistent for Falls Church when normalized by time.

The two methods were consistent for 11 of the 14 cases. In Falls Church, they were consistent when normalized by ADT, and in the remaining four jurisdictions, they were consistent regardless of how the results were normalized. For example, as shown in Table 13, a net positive impact of 90,555 was shown for Alexandria for the first method whereas a net positive impact of 130,557 was shown for the second method. Further, when all results were aggregated across all jurisdictions, the two methods for linking KABCO gave similar results, again regardless of whether the results were normalized by time or ADT.

Overall, therefore, the results using the two methods appeared to be consistent for most (80%) of the cases. There are no obvious reasons the results for 3 of the 14 cases (both Fairfax City cases and Falls Church normalized time) were inconsistent. A contributing factor might be that in these three cases, the cameras had a moderate rather than a dramatic impact on the change in comprehensive crash costs in these three jurisdictions. For example, if the absolute value of the net change in comprehensive crash cost when normalized by time is ranked, the two lowest absolute values (Fairfax City and Falls Church) were the two inconsistent cases when normalized by time. Thus it may be the case that, as expected, different scales will yield different results and the results are most likely to change direction when the initial results are relatively close to zero.

Sensitivity Test 6: Feasibility of Using Virginia-Specific Injury Data Instead of National Injury Data

The investigators found that the use of Virginia-specific injury data was not feasible because of the small sample of available Virginia data, as demonstrated in Appendix J and summarized here.

The first approach examined was to use detailed hospital data to derive costs for Virginia crashes. Based on the 2001–2002 dataset, highly detailed injury information (total hospital charges, length of stay, abbreviated injury score, and injury severity score) is available only for about 3% of the total crashes at the selected Northern Virginia intersections. In contrast, officers at the crash scene indicated an injury had occurred in approximately 38% of the total crashes. This approach was therefore abandoned.

An alternative approach—evaluating the net severity impacts for specific crashes—was also hampered by a lack of data. For example, based on the 2001–2002 dataset, there were 132 injury crashes at intersections where a camera had been installed at some point from January 1, 2001, to December 31, 2002. However, detailed hospital data were available for only 10 such crashes. This analysis was therefore abandoned.

Sensitivity Test 7: Rear-end Crash Frequency in Fairfax County

Some observers had hypothesized that the increase in rear-end crashes attributed to cameras was only temporary. The hypothesis is that such crashes might immediately increase following installation of the cameras and then gradually decrease as drivers became accustomed to the cameras. To investigate this hypothesis, the frequency of rear-end crashes in the jurisdiction with the largest photo-red enforcement program—Fairfax County—was studied.

Overall, the results did not confirm the hypothesis. As shown in Figure 2, the percentage of rear-end crashes per month did not decrease over time following the month of camera installation (reflected as Month 0).

There were a few intersections where a graph of rear-end crashes suggested that such rear-end crashes might not necessarily increase overall in the very long term. One such intersection is shown in Figure 3 (Lee Jackson Highway and Rugby/Middle Ridge Road) where the number of rear-end crashes appears to be returning to the levels prior to camera installation. These intersections may merit further investigation in the future.

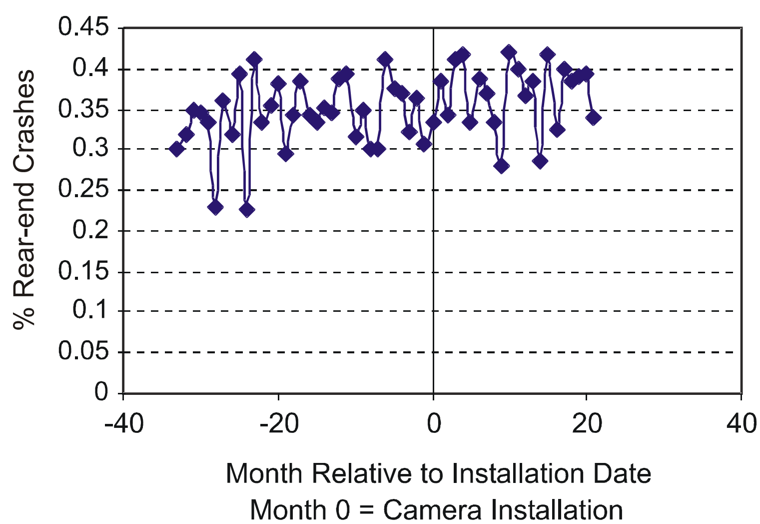

Figure 2. Percentage of Crashes That Were Rear-end Crashes (aggregate data for all intersections in Fairfax County). Month 0 is the month of camera installation for each intersection.

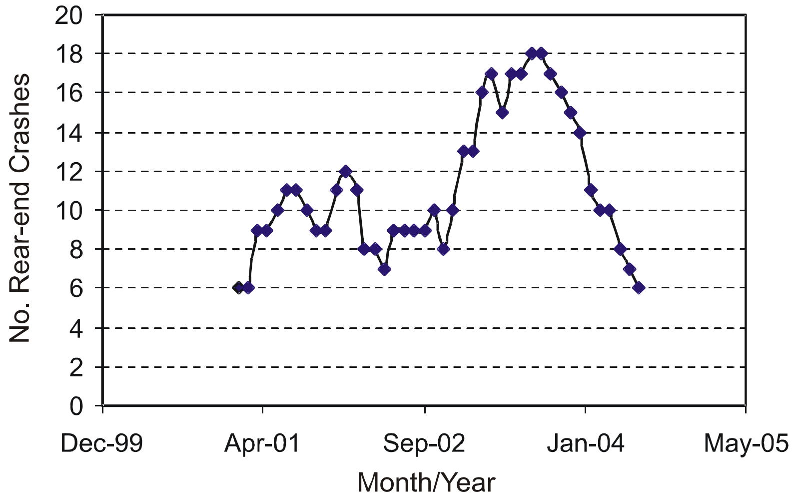

Figure 3. Change in Number of Rear-end Crashes at Intersection of Lee Jackson Highway and Rugby/Middle Ridge Following Camera Installation in February 2001

Sensitivity Test 8. Injury Severity and Types of Restraints Used in Fairfax County

The results of the injury severity analysis did not show a statistically significant change in crash severity based on the officer's indication at the scene of the crash ($p = 0.51$ for restrained occupants and $p = 0.27$ for unrestrained occupants).

There was *generally* a nonsignificant decrease in crash severity for both restrained and unrestrained occupants, however, as shown in Tables 21 and 22. Table 21 shows that *except for fatal crashes*, the severity of injuries sustained as a result of crashes at camera intersections in Fairfax County decreased after camera installation for crashes where safety restraints were used. (The decrease was not significant.) This can be seen in the decrease in Type 2 and Type 3 injuries and the increase in Type 4 injuries. The exception is the fatal crashes (shown as Type 1): there were two Type 1 injuries after camera installation, one of which occurred 4 days after camera installation. Table 22 also shows a benefit of the cameras, with a decrease in Type 1 and Type 2 injuries and an increase in Type 3 and Type 4 injuries after camera installation, and the benefit is more pronounced than that of Table 21 as the few fatalities are eliminated.

The results shown in Tables 21 and 22 also support those in the comprehensive crash cost analysis shown in Tables 13 and 15 and in the statistical analysis shown in Table 12. Table 12

Table 21. Injury Distribution for Crashes with Safety Restraints Used[a]

Period	Injury Type			
	1 (Fatal, Most Severe)	**2**	**3**	**4 (Least Severe)**
Before	0	0.211886	0.087855	0.700258
After	0.005797	0.17971	0.081159	0.733333

[a]For the driver to have been considered to be using proper safety restraints, the FR 300 police report must have classified the driver as using a lap belt, harness, or lap belt and harness.

Table 22. Injury Distribution for Crashes with No Safety Restraints Used[a]

Period	Injury Type			
	1 (Fatal, Most Severe)	2	3	4 (Least Severe)
Before	0.044118	0.308824	0.132353	0.514706
After	0	0.2125	0.2	0.5875

[a]For the driver to have been considered to be using proper safety restraints, the FR 300 police report must have classified the driver as using a lap belt, harness, or lap belt and harness.

showed that the paired sample *t*-test indicated a nonsignificant increase in Fairfax County injury crashes. In Table 13, normalization by time indicated that the cameras were associated with a $400,602 increase in comprehensive crash costs for injury crashes. It is thus logical that the increase in injury crashes in Table 12 would lead to an increase in costs based on such crashes in Table 13.

However, Table 15 shows an $8,539 reduction in comprehensive crash costs for a subset of-crashes for Fairfax County. This subset of crashes are those crashes when the Severity Indices A, B, and C were used (which correspond to Injury Types 2, 3, and 4). The reason Table 15 thus shows lower crash costs than Table 13 for Fairfax County is attributed to the decrease in severity noted in Tables 21 and 22. That is, given that a pool of injury crashes occurred, the portions that are most severe were lower after camera installation as compared to before camera installation.

CONCLUSIONS

Eleven conclusions regarding the impact of cameras on crash frequency may be drawn. For the sake of consistency, Conclusions 3 through 8 were based primarily on the results obtained from the EB method, which is generally considered to be the most accurate of the four methods employed. However, it is known that the EB approach may not yield reliable results when only a few sites comprise the dataset; hence, this analysis is complemented with the GLM and paired *t*-test results as necessary.

1. *The cameras did not have the same associated impact in all jurisdictions.* Although some trends are evident as noted in Conclusions 3 through 8, there were two substantial outliers. The EB results showed that the cameras were associated with an increase in all six crash types in Arlington County, five of which were significant. In Fairfax City, in contrast, the cameras were not associated with any significant increases; they were associated with a significant decrease for three crash types. For this reason, "average" changes may not be good predictors of performance at a particular intersection. For example, although the EB results suggested that cameras were associated with an increase of between 31% and 54% for rear-end crashes overall, this range does not even include the point estimate of the impact of rear-end crashes in four of the five jurisdictions studied: Arlington (139%), Fairfax City (10%), Falls Church (136%), and Vienna (64%).

2. *The cameras did not have the same associated impact even within a single jurisdiction*. For example, in Fairfax County, there were four intersections where injury crash rates (number of crashes per intersection-year multiplied by ADT) decreased yet five intersections where injury crash rates increased. Similarly, of the four intersections in Fairfax City where such a rate could be determined, two showed an increase and two showed a decrease.

3. *The cameras were associated with an increase in rear-end crashes*. The EB method showed a significant increase in four of the five jurisdictions and a nonsignificant increase in one jurisdiction (Fairfax City). To the extent an average is useful (see Conclusion 1), the EB results suggest that the point estimate of this increase is 42%. A simple before-after comparison after normalizing by time and ADT suggested an average increase of 27% by intersection.

4. *The cameras were associated with a decrease in red light running crashes*. In two jurisdictions (Fairfax City and County), there was a significant decrease; in one jurisdiction (Vienna), there was a nonsignificant decrease; and in Falls Church, there was a nonsignificant increase. The exception was Arlington, which showed an increase for *all* crash types. When all results were aggregated, the EB method gave a point estimate of an 8% decrease, with the confidence interval ranging from a 22% decrease to a 7% increase. A simple before-after comparison after normalizing by time and ADT suggested an average decrease of 42% by intersection.

5. *The cameras were associated with a decrease in injury red light running crashes*. Two jurisdictions saw a significant decrease (Vienna and Fairfax City), one saw a nonsignificant decrease (Fairfax County), and two saw nonsignificant increases (Arlington and Falls Church). The aggregate EB results suggested a point estimate of a 7% *increase*, with the range between an 18% decrease and a 31% increase. However, given the jurisdiction-by-jurisdiction results (e.g., decreases noted in Fairfax City, Fairfax County, and Vienna); the fact that the GLM showed decreases in all jurisdictions except Arlington (in Fairfax City, GLM suggested that cameras were associated with an increase only when truck percentages were high, i.e., about 40% of the cases); and the fact that a simple before-after comparison after normalizing by time and ADT suggested an average decrease of 28% by intersection, the data suggested that cameras were associated with a decrease.

6. *The cameras were associated with an increase in total crashes.* Arlington and Fairfax County saw significant increases, Falls Church and Vienna saw nonsignificant increases, and Fairfax City saw a nonsignificant decrease. The aggregate EB results suggested that this increase was 29%, whereas a simple before/after comparison that controlled for time and ADT suggested an increase of 12% per intersection.

7. *The association of the cameras with angle crashes differed among jurisdictions, although a preponderance of test results suggested an increase.* A significant increase occurred in Arlington, and an offsetting significant decrease occurred in

Fairfax City. Fairfax County saw a nonsignificant increase, whereas Falls Church and Vienna saw a nonsignificant decrease. The aggregate EB results suggested a 20% increase, whereas a simple before/after comparison that controlled for time and ADT suggested a 6% *decrease* per intersection.

8. *The cameras were associated with an increase in the frequency of injury crashes.* Significant increases were noted in Arlington and Vienna, nonsignificant increases were noted in Falls Church and Fairfax County, and a nonsignificant decrease was noted in Fairfax City. The aggregate EB results suggested an 18% increase, although the point estimates for individual jurisdictions were substantially higher (59%, 79%, or 89% increases) or lower (6% increase or a 5% decrease). Further, a simple before/after comparison suggested a 10% decrease per intersection. Although the number of Fairfax County injury crashes increased, the cameras were associated with a nonsignificant decrease in the *severity distribution* of those injury crashes, for both occupants using safety equipment (p = 0.51) and occupants not using safety equipment (p = 0.27).

9. *The results of the comprehensive crash cost analysis varied based on the assumptions and jurisdictions used.* Because rear-end crashes increased and red light running crashes decreased as a function of camera installation, the comprehensive crash cost analysis shown in Tables 13, 14, and 15 shows a range of possibilities based on comparing angle and rear-end crashes after camera installation. These results suggest that the cameras were associated with the following:

    - when results for all six jurisdictions and all crashes (injury and noninjury) were combined, a net negative impact as shown in the bottom row of Tables 13 and 14

    - when all crashes (injury and noninjury) were combined, a net positive impact for two jurisdictions (Alexandria and Vienna), a net negative impact for two jurisdictions (Arlington and Fairfax County), and mixed results for two jurisdictions (Fairfax City and Falls Church); for the last two jurisdictions, factors affecting the results were normalizing by time or ADT (Falls Church), whether injury crashes were categorized by severity or treated uniformly (Fairfax City and Falls Church), and the manner in which the Virginia severities of 1, 2, 3, and 4 recorded by the officer were linked to KABCO (Fairfax City and Falls Church)

    - a net positive impact for injury-only crashes only in some jurisdictions (Alexandria, Fairfax City, and Vienna) and a net negative impact for injury-only crashes in others (Arlington, Fairfax County, and Falls Church)

    - a net positive impact for injury crashes when all jurisdictions were combined and the officer's indication of severity was used (thus linking injury crashes to KABCO injury severity levels A, B, and C), provided the three fatal crashes in Fairfax County were excluded from the analysis

- either a net positive or net negative impact for injury crashes when all jurisdictions were combined and injury severity levels were not used

- a net negative impact for noninjury crashes except in Falls Church, where they were associated with a net positive impact.

10. *Methodologically, the statistical tests employed usually, but not always, gave consistent results*. Of 30 cases where an inconsistency was feasible (six crash types multiplied by five jurisdictions), there were no direct conflicts (where one test showed a statistically significant increase and another test showed a statistically significant decrease) and there were nine moderate conflicts (where one test yielded a statistically significant increase and another yielded a nonsignificant decrease or vice-versa).

11. *The cameras were not associated with a decrease in rear-end crashes over time after the initial increase that followed camera installation*. It had been hypothesized that a large increase in rear-end crashes after camera installation might be followed by a decrease in rear-end crashes after motorists became habituated to the camera, but no such change was observed (see Figure 2). This conclusion is limited by the fact that only crashes in Fairfax County were studied and the after period was at most a few years long.

RECOMMENDATIONS

Summary

Two recommendations are summarized here and detailed on the pages that follow.

1. *Red light cameras should not be implemented without an intersection-specific study of the intersection's crash patterns and geometric characteristics.* Table 23 gives examples of how to interpret these characteristics to determine whether or not to install a camera at a particular intersection.

2. *Because of the opportunity to identify the geometric and operational characteristics of intersections that could adversely affect the safety impacts of red light cameras, it is recommended that additional controlled studies be conducted at those intersections where red light cameras have been installed.* Two strategies for conducting this necessary additional research are given.

Statewide legislation (HB 1778) allows localities, at their discretion, to use one red light camera per 10,000 residents (Virginia General Assembly Legislative Information System, 2007). However, because the results of this study show that the characteristics at specific intersections may affect the effectiveness of the cameras, additional research is still warranted. The intent of Recommendation 2 is that any entity—state, regional, or local—that chooses to establish a photo-red program should participate in a carefully controlled experiment to monitor the crash impacts of the program and use the results to identify the geometric and traffic characteristics that positively or negatively affect the impact of the implementation of the red light cameras.

Full Text of Recommendations with Implementation Examples

1. *Red light cameras should be implemented on a case-by-case basis and only after a careful review of the crash patterns (rear-end crashes, red light running crashes, and injury crashes) and geometric/operational characteristics (e.g., approach speeds, intersection visibility, signing, and driveways) at each intersection where they are placed.* Two important results led to this recommendation: Within some jurisdictions, at certain intersections and for some crash types, the cameras were shown to be associated with beneficial effects. Examples are decreased red light running crashes in Fairfax City and Fairfax County and decreased comprehensive crash costs in Alexandria and Vienna. On the other hand, when red light cameras were installed at some intersections, they were shown to be associated with a reduction in safety. Further, when the data from all intersections were combined into a single dataset, cameras were not found to be associated with a reduction in injury crashes and comprehensive crash costs. Table 23 illustrates how this recommendation may be implemented.

2. *Because of the opportunity to identify the geometric and operational characteristics of intersections that could adversely affect the safety impacts of red light cameras, it is recommended that additional controlled studies be conducted at those intersections where red light cameras have been installed.* This additional research may be accomplished using Strategy A and/or Strategy B:

    - *Strategy A: Determine whether the improved safety at the seven specific intersections listed in Appendices B and C was definitively associated with the use of the cameras.* After cameras were installed at these intersections, total injury crashes decreased, red light running crashes decreased, and rear-end crashes either decreased or moderately increased. Because the cameras were eliminated after June 30, 2005, it may also be possible to determine if the safety benefits degraded at these intersections. The research should compare the characteristics of these intersections with those of others in the study where the cameras were associated with a net negative effect. These seven intersections are:

        — Lee Jackson Highway and Fair Ridge Drive (Fairfax County)
        — Lee Jackson Highway and Rugby/Middle Ridge (Fairfax County)
        — Leesburg Pike and Westpark/Gosnell (Fairfax County)
        — Route 7 and Carlin Springs (Fairfax County)
        — West Broad Street and Cherry Street (Falls Church)
        — Maple Avenue East and Follin Lane (Vienna)
        — Route 123 and North Street (Fairfax City) (where the rear-end crash rate increased more than at the other six intersections but injury rates still decreased).

Table 23. Examples for Implementing Recommendation 1

Situation	Resolution
Elected officials in City A suggest that red light cameras be installed, but the city has insufficient staff to study each intersection.	City A may decide not to install red light cameras until engineering staff can be hired.
At Intersection B, the mainline has a speed limit of 45 mph and observed speeds of 55 mph. There is limited red light running and some rear-end crashes.	The jurisdiction may decide not to install red light cameras because they are generally associated with an increase in rear-end crashes and an increase in such crashes at speeds of 55 mph might dramatically increase injury risk.
At Intersection C, the number of rear-end crashes has remained constant over the past 5 years but red light crashes have increased significantly. An engineering study shows that sight distances exceed those prescribed in the standard guidelines, that the 12-inch signal heads are clearly visible, and that the length of the yellow plus all red phase exceeds the recommendations of the Institute of Traffic Engineers (1999).	The jurisdiction may decide to install red light cameras at this location but monitor the crash results closely by measuring the number of rear-end and red light running crashes every month. In addition, engineers visit the site for 1 hour each month to observe driver behavior.
After 6 months with the camera installed at Intersection C, rear-end crashes have increased significantly. Site visits reveal that many of the crashes occur on the eastbound approach during the morning rush hour where a leading vehicle brakes sharply at the onset of the yellow indication and a trailing vehicle strikes the lead vehicle.	The jurisdiction stations a visible law enforcement officer 800 feet upstream of the intersection during the morning rush hour to reduce tailgating before the intersection. The jurisdiction also posts larger red light camera signs 1,000 feet upstream of the intersection. Staff also monitor the intersection during the morning peak hour, checking whether any of the following contributes to the increase in rear-end crashes:: (1) heavy sunlight making the signal difficult to see, (2) heavy trucks obscuring the signal, and (3) commercial driveways within 300 feet of the signal.
Same situation as Intersection C except that resources for additional funds and an engineering study are not available.	The jurisdiction may discontinue the program at this intersection.
At Intersection D, 20 injury crashes have occurred over the past 3 years: 12 were red light running, 4 were rear-end, and 4 were run-off-the-road crashes. In addition, 30 non-injury rear-end crashes have occurred over the past 3 years, suggesting a rate of 5 such crashes every 6 months. No deficiencies (intersection sight distance, signal head visibility, yellow timing, presence of commercial driveways within 300 feet of the intersection) are noted in a site-specific study.	The jurisdiction tentatively initiates a program but only after finding that all 4 run-off-the-road crashes involved alcohol and not poor visibility at the intersection. The jurisdiction carefully monitors rear-end crashes over the next 6 months, recognizing that based on previous data in the previous period, roughly 5 non-injury rear-end crashes might be expected. If a substantially higher number (say, 7) is noted in the first 6 months, even if the rear-end crashes are non-injury, the intersection should be studied again.
At Intersection E, red light running crashes are increasing. Law enforcement officers cannot safely stop red light runners because of heavy congestion at the intersection.	Several safety countermeasures are considered, including traditional law enforcement, adjustments to the signal timing, and installation of a red light camera. It is found that a longer yellow time is warranted. Thus, the yellow time is lengthened. No red light cameras are installed.
At Intersection E, red light running crashes continue to occur 6 months after the length of the yellow time was extended.	The city decides to install and monitor the impact of a red light camera system.
At Intersection F, red light running crashes are increasing. Law enforcement officers cannot safely stop red light runners because of heavy congestion at the intersection.	As with Intersection E, several safety countermeasures are considered. An engineering study as per Recommendation 1 yields no geometric defects (such as poor signal visibility or an insufficient yellow time). Thus, a red light camera is installed.

- *Strategy B: Conduct a carefully controlled experiment at particular additional intersections that have been selected for the installation of cameras to examine further the impact of red light programs on safety.* Because of the extreme variation in crash history at the various intersections, further data attained through carefully controlled experiments are required to assess definitively the intersection characteristics that influence the effectiveness of red light cameras in reducing the number and severity of crashes and to determine the most beneficial locations for their placement. These data should be collected so that an evaluation may be performed in accordance with generally accepted scientific principles such as the establishment of control sites; the identification of treatment sites that address confounding factors; and the comparison of crash frequency and severity between treatment and control sites. The researchers believe that the use of approximately 24 to 48 intersections, a comparable number of control sites, and 3 to 5 years of data would be sufficient for a scientifically defensible study. This additional research could be conducted by any one of several entities that have an interest in how red light cameras are operated. Such entities include, but are not limited to, an individual jurisdiction, a group of jurisdictions, a regional body such as a planning district commission, a public interest group, a branch of the federal government, a university, a national research funding body such as the National Cooperative Highway Research Program, or any other entity that seeks to understand better the factors that influence the safety impacts of red light camera programs.

Note that each strategy is designed to identify the reasons red light cameras were associated with adverse safety impacts at some intersections but not others—reasons that have not yet been conclusively identified. If no jurisdictions choose to implement red light cameras, then Strategy A will be more productive. If many jurisdictions choose to implement red light cameras, then Strategy B will be more productive. If some jurisdictions do and some do not choose to implement red light cameras, then a mix of these two strategies should be used.

COSTS AND BENEFITS ASSESSMENT

This study focused exclusively on the impacts of red light cameras on crashes; it did not estimate other types of impacts, such as the amount of money required to operate a red light camera program. If the spirit of Recommendation 2 (Strategy B) is kept—i.e., a carefully controlled experiment to evaluate the impacts of red light cameras on crashes is conducted prior to initiating a program—following the recommendation will yield a cost and benefit.

The cost of such an experiment would have two components: (1) the monetary cost of the experiment and (2) the risk that a program would be established that would increase the risk of crashes. Considering only the first component, with 36 treatment sites, 36 control intersections, and a 4-year data collection period, the cost of the experiment might be estimated as $400,000. Considering the second component, the cost might range from 0 (the cameras did not adversely affect safety where they were deployed on an experimental basis) to as high as $3 million per intersection-year (assuming the very worst case scenario from Table ES2 and assuming cameras adversely affected safety at each intersection).

The benefit of such an experiment would be a better understanding of where red light cameras would be effective and where they would not be effective. This benefit may be roughly quantified by considering two intersections from Fairfax County.

- At one intersection (Leesburg Pike and Westpark/Gosnell) the cameras were associated with a *reduction* in comprehensive crash costs of $33,416 per intersection-year.

- At another intersection (Leesburg Pike and Towlston Road) the cameras were associated with an *increase* in comprehensive crash costs of $34,741 per intersection-year.

Based on this knowledge, a red light camera program would be initiated at the Leesburg Pike and Westpark/Gosnell intersection (thereby reducing comprehensive crash costs by $33,416 per intersection-year) but not at Leesburg Pike and Towlston Road (thereby avoiding an increase in comprehensive crash costs of $34,741 per intersection-year).

Suppose that localities in Virginia are considering the implementation of red light cameras at 50 intersections in Virginia. Suppose further that half of Virginia's intersections are comparable to Leesburg Pike and Westpark/Gosnell (where a camera improves safety), and suppose that the other half of Virginia's intersections are comparable to Leesburg Pike and Towlston Road (where the camera hinders safety).

A completely wrong decision would be to perform two actions.

- *Install cameras at the 25 intersections comparable to Leesburg Pike and Towlston Road.* The cost of installing these cameras (at a location where the cameras are associated with an increase in comprehensive crash costs of $34,741 per intersection-year), would be (25 intersections)($34,741 per intersection-year) = $868,525 per year.

- *Not install cameras at the 25 intersections comparable to Leesburg Pike and Westpark/Gosnell.* The cost of not installing cameras at these locations (where a camera would be associated with a reduction in comprehensive crash costs) would be (25 intersections)($33,416 per intersection-year) = $835,400 per year.

Thus the total cost of this wrong decision would be $868,525 + $835, 400 = $1,703,925 per year. Relative to this "wrong" decision, correct knowledge of where to place cameras will save $1,703,925 per year. (That is, the "right" decision would be to place the cameras at the 25 intersections comparable to Leesburg Pike and Westpark/Gosnell but not place them at Leesburg Pike and Towlston Road.)

If the results of the proposed experiment from Recommendation 2 (Strategy B) were thus applied at 50 intersections over a 4-year period—the benefits may be estimated as ($1,703,925 per year)(4 years) = $6.8 million over the 4-year period. Clearly this potential savings is an order of magnitude estimate only. The actual savings may be more or less depending on (1) the number of intersections considered, (2) the percentage of intersections where cameras are beneficial relative to those where cameras are not beneficial, and (3) the extent to which the cost savings for the two chosen intersections for this example represent cost savings at other intersections in Virginia.

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APPENDIX A

INTERSECTIONS STUDIED IN THIS REPORT

Table A1. Camera Intersections by Jurisdiction

Intersection	Jurisdiction	Camera Direction	Installation Date
Duke & South Walker St.	Alexandria	EB	November 1997
Duke & West Taylor Run Pkwy (only this intersection was used from Alexandria)	Alexandria	WB	March 2004
Gibbon St. & Route 1 (S. Patrick St.)	Alexandria	SB	November 1997
Seminary Rd. & Mark Center/Nottingham	Alexandria	NWB	November 1997
Route 50 & Fillmore St.	Arlington	EB	February 1999
Route 50 & Manchester St.	Arlington	WB	July 2001
Wilson Blvd. & Lynn St.	Arlington	EB	February 1999
Lynn St. & Lee Hwy	Arlington	NB	June 2000
Route 1 & 27th St.	Arlington	SB	July 2001
Rt. 50 & Lee Hwy/Old Lee Hwy & Fairfax Circle	Fairfax City	WB	July 1997
Rte. 123 & Eaton Place	Fairfax City	SB	July 1997
Rte. 29/50 & Rte. 123	Fairfax City	EB	May 1998
Rte. 123 & North St.	Fairfax City	NB	May 1998
Rte. 50 & Jermantown Rd.	Fairfax City	WB	May 1998
Rte. 29/50 & Plantation Pkwy	Fairfax City	EB	May 1998
Rte. 236 & Pickett Rd.	Fairfax City	WB	May 1998
Arlington Blvd. & Jaguar Trail	Fairfax County	WB	May 2001
Fairfax County Pkwy & Newington Rd.	Fairfax County	NB	October 2001
Fairfax County Pkwy & Popes Head Rd.	Fairfax County	SB	July 2001
Lee Jackson Hwy & Fair Ridge	Fairfax County	WB	February 2001
Lee Jackson Hwy & Rugby/Middle Ridge	Fairfax County	WB	February 2001
Leesburg Pike & Dranesville Rd.	Fairfax County	EB	June 2001
Leesburg Pike & Route 66	Fairfax County	WB	May 2001
Leesburg Pike & Towlston Rd.	Fairfax County	EB	October 2000
Leesburg Pike & Westpark/Gosnell[a]	Fairfax County	WB	March 2001
Route 236 (Little River) & Heritage/Hummer	Fairfax County	EB	September 2002
Route 28 (Centreville) & Green Trails/Old Mill	Fairfax County	SB	June 2001
Route 7 & Carlin Springs	Fairfax County	WB	March 2003
Telegraph & Huntington/95/495	Fairfax County	NB	March 2003
W. Broad St. (SR 7) & Annandale Rd.	Falls Church	EB	October 2001
W. Broad St. (SR 7) & Birch St.	Falls Church	EB/WB	May 2002
W. Broad St. (SR7) & Cherry St.	Falls Church	EB/WB	July 2004
Maple Ave E. & Follin Lane	Vienna	EB/WB	June 1999
Maple Ave W. & Nutley St.	Vienna	EB/WB	September 2003
Maple Ave W. & Glyndon St.	Vienna	EB/WB	May 2004

[a]At some point, a second camera was installed at this location (B. Otten, personal communication by email, 9:16 a.m., May 31, 2006).

Table A2. Comparison Intersections by Jurisdiction

Intersection	Jurisdiction
Duke & South Reynolds St.	Alexandria
Duke & Jordan St.	Alexandria
Route 1 (S. Patrick St.) & Franklin St.	Alexandria
Route 50 & Pershing Dr.	Arlington
Wilson Blvd. & George Mason Dr.	Arlington
Columbia Pike (244) & Walter Reed Dr.	Arlington
Main St. (236) & Burke Station Rd. (652)	Fairfax City
Main St. (236) & Lee Hwy (29/50)	Fairfax City
Lee Hwy (29/50) & Stafford Dr.	Fairfax City
Braddock (620) & Kings Park (3294)	Fairfax County
Braddock (620) & Port Royal (3090)	Fairfax County
Braddock (620) & Queensbury (3247)	Fairfax County
Braddock (620) & Southhampton (3647)	Fairfax County
Braddock (620) & Wakefield Chapel (710)	Fairfax County
Chain Bridge (123) & Jermantown (655)	Fairfax County
Chain Bridge (123) & Old Courthouse (655)	Fairfax County
Dolley Madison Blvd. (123) & Old Chain Bridge Rd. (687)	Fairfax County
Dolley Madison Blvd. (123/309) & Old Dominion (738)	Fairfax County
Lawyers (644) & West Ox (608)/Folkstone (5640)	Fairfax County
Lee Hwy (29) & Circle Woods (5996)	Fairfax County
Lee Hwy (29) & Nutley (243)	Fairfax County
Nutley (243) & Hermosa Dr. (2025)	Fairfax County
Nutley (243) & Swanee/Metro So. (3238)	Fairfax County
Old Keene Mill (644) & Greeley Blvd. (3332)	Fairfax County
Old Keene Mill (644) & Hanover Ave. (1193)	Fairfax County
Old Keene Mill (644) & Huntsman (4521)	Fairfax County
Reston Pkwy (602) & Bluemont/Market (7199)	Fairfax County
Reston Pkwy (602) & Bowmantown/Bowmangreen (6337)	Fairfax County
Reston Pkwy (602) & Sunset Hills (675)	Fairfax County
Reston Pkwy (602) & Temporary Rd./New Dominion (6363)	Fairfax County
Sully Rd. (28) & Westfields Blvd. (6755)	Fairfax County
Sully Rd. (28) & Braddock (620)/Walney (657)	Fairfax County
Sully Rd. (28) & Willard (6215)	Fairfax County
Van Dorn (613) & Crown Royal (8110)	Fairfax County
Van Dorn (613) & Franconia (644)	Fairfax County
Van Dorn (613) & Oakwood (10019)	Fairfax County
Van Dorn (613) & Woodfield/Chrysanthemum (8400)	Fairfax County
West Ox (608) & Fairlakes Pkwy (7700)	Fairfax County
West Ox (608) & Monument Dr. (6751)	Fairfax County
West Ox (608) & Piney Branch Rd./Transfer (6187)	Fairfax County
West Ox (608) & Price Club Connector Rd. (6187)	Fairfax County
West Ox (608) & Cedar Lakes (608/8376)/Hanger (4901)	Fairfax County
E. Broad St. (SR7) & Roosevelt (6792)	Falls Church
W. Broad St. (SR7) & North West (6749)	Falls Church
W. Broad St. (SR7) & Little Falls (6797)	Falls Church
Maple Ave. & Lawyers St.	Vienna
Maple Ave. & Center St.	Vienna
Maple Ave. & East St.	Vienna

Table A3. Spillover Intersections by Jurisdiction

Intersection	Jurisdiction	Camera Intersection	Distance from Camera Intersection
Lee Hwy (29/50) & Stafford Dr.	Fairfax City	Rte. 29 & 50 /Plantation Pkwy	0.15 mi
Lee Hwy (29/50) & McLean/Warwick	Fairfax City	Rte. 29/50 & Rte. 123	0.27 mi
Lee Hwy (29/50) & University	Fairfax City	Rte. 29/50 & Rte. 123	0.21 mi
Lee Hwy (29/50) & University	Fairfax City	Rte. 29/50 & Plantation Pkwy	0.59 mi
Leesburg Pike (SR 7) & FR 773	Fairfax County	Leesburg Pike (SR 7) & Westpark Dr.	0.30 mi
Leesburg Pike (SR 7) & Spring Hill	Fairfax County	Leesburg Pike (SR 7) & Westpark Dr.	0.35 mi
E. Broad St. (SR 7) & Roosevelt	Falls Church	W. Broad St. & Cherry St.	0.45 mi
W. Broad St. (SR 7) & North West	Falls Church	W. Broad St. & Birch St.	0.30 mi
W. Broad St. (SR 7) & Little Falls	Falls Church	W. Broad St. & Annandale Rd.	0.08 mi
Broad St. (SR 7) & Haycock (703)	Falls Church	W. Broad St. & Birch St.	0.15 mi
Broad St. (SR 7) & Virginia Ave.	Falls Church	W. Broad St. & Annandale Rd.	0.08 mi
Broad St. (SR 7) & Washington Ave.	Falls Church	W. Broad St. & Cherry St.	0.30 mi
Maple Ave. (SR 123) & Branch Rd.	Vienna	Maple Ave. & Glyndon St.	0.30 mi
Maple Ave. (SR 123) & Park St.	Vienna	Maple Ave. & Glyndon St.	0.20 mi
Chain Bridge Rd. (123) & Flint Hill	Vienna	Maple Ave. & Nutley St.	0.42 mi
Maple Ave. & Lawyers St.	Vienna	Maple Ave. & Nutley St.	0.50 mi

Table A4. Summary: Approximate Number of Intersections Used in Study[a]

Jurisdiction	Camera Intersections	Comparison Intersections	Total (Camera + Comparison)	Spillover Intersections
Alexandria	1	N/A	Used only in crash severity computations	N/A
Arlington	4	2	6	None
Fairfax City	5	3	8	3
Fairfax County	13	33	46	2
Falls Church	3	3	6	6
Vienna	3	3	6	4

[a]Totals vary slightly throughout the report based on the particular test employed. For example, Table A4 shows a total of 46 Fairfax County sites. For tests that used only major ADT, this number is correct. However, only 40 of the 46 sites had an ADT on the minor approach—thus, for tests that required use of the minor ADT, the number of Fairfax County sites was 40 rather than 46.

Table A5. Number of Crashes by Type and Jurisdiction for Camera Intersections[a,b]

Jurisdiction (Intersections in the total)	Rear-end		Red Light Running		Angle		Injury Red Light Running		Injury		Total	
	Before Camera	After Camera	Before Camera	After Camera	Before Camera	After Camera	Before Camera	After Camera	Before Camera	After Camera	Before Camera	After Camera
Alexandria (1)	90	14	6	0	14	1	3	0	50	5	115	20
Arlington (4)	56	126	26	65	59	122	14	33	65	148	133	301
Fairfax City (7)[b]	11	421	8	103	12	437	2	41	11	297	25	983
Fairfax County (13)	399	494	127	61	393	285	64	31	326	331	891	861
Falls Church (3)	26	16	11	6	37	11	6	4	25	19	78	34
Vienna (3)	82	72	15	1	53	18	6	0	60	31	151	97

[a]The number of before (and after) crashes at each intersection were summed to give the totals shown in Table A5. Each intersection had a unique camera installation date, and therefore the totals must be examined in light of the total intersection-years for the jurisdiction. The total before and after intersection-years by jurisdiction are as follows: Alexandria 6.17 and 0.83 (for the single intersection); Arlington 10.5 and 17.50; Fairfax City 1.67 and 47.33; Fairfax County 47.92 and 43.08; Falls Church 14.58 and 6.42; and Vienna 13.57 and 7.43.

[b]Note that for Fairfax City, two of the intersections shown in this total (one being Rt. 50 & Lee Hwy/Old Lee Hwy & Fairfax Circle and the other being Rte. 123 & Eaton Place) had cameras installed before January 1, 1998 which meant that those two cameras had no before data. Accordingly, they were not included in the analysis. For example, for the five remaining Fairfax City intersections, the after-camera rear-end crashes were 347 and the after-camera angle crashes were 272.

APPENDIX B

IMPACT OF CAMERAS ON CRASHES, NORMALIZED BY TIME

Table B1. Arlington Camera Site Crash Rates Normalized by Time (Crashes per Intersection Year)

Intersection	Rear-end		Red Light Running		Angle		Injury Red Light Running		Injury		Total	
	Before Camera	After Camera	Before Camera	After Camera	Before Camera	After Camera	Before Camera	After Camera	Before Camera	After Camera	Before Camera	After Camera
Route 50 & Fillmore St.	5.56	9.80	1.85	1.86	4.63	4.39	0.93	0.84	8.33	7.94	14.81	16.72
Route 50 & Manchester St.	10.00	12.83	2.86	2.86	6.29	7.71	1.43	2.29	8.00	12.86	17.14	22.29
Wilson Blvd. & Lynn St.	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Lynn St. & Lee Hwy	2.48	2.18	5.79	8.95	10.74	13.32	3.31	3.93	7.85	9.17	16.12	21.83
Route 1 & 27th St.	2.57	3.71	0.00	0.86	1.71	2.29	0.00	0.57	2.57	4.00	5.15	6.86

Table B2. Arlington Comparison Site Crash Rates Normalized by Time (Crashes per Intersection Year)

Intersection	Rear-end		Red Light Running		Angle		Injury Red Light Running		Injury		Total	
	Before Camera	After Camera	Before Camera	After Camera	Before Camera	After Camera	Before Camera	After Camera	Before Camera	After Camera	Before Camera	After Camera
Route 50 & Pershing Dr.	5.54	2.37	1.85	1.35	9.23	4.90	0.00	0.68	9.23	5.07	15.69	9.46
Wilson Blvd. & George Mason Dr.	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Columbia Pike (244) & Walter Reed Dr.	1.85	2.70	0.00	0.85	2.77	3.72	0.00	0.00	5.54	3.55	8.31	10.14

Table B3. Fairfax City Camera Site Crash Rates Normalized by Time (Crashes per Intersection Year)

Intersection	Rear-end		Red Light Running		Angle		Injury Red Light Running		Injury		Total	
	Before Camera	After Camera	Before Camera	After Camera	Before Camera	After Camera	Before Camera	After Camera	Before Camera	After Camera	Before Camera	After Camera
Rt. 50 & Lee Hwy/Old Lee Hwy & Fairfax Circle	N/A	6.14	N/A	3.14	N/A	13.00	N/A	0.86	N/A	4.86	N/A	23.71
Rte. 123 & Eaton Place	N/A	4.43	N/A	2.00	N/A	10.57	N/A	1.43	N/A	6.43	N/A	16.29
Rte. 29/50 & Rte. 123	12.12	14.09	6.06	2.55	9.09	12.59	0.00	1.50	9.09	10.19	24.24	29.99
Rte. 123 & North St.	3.03	5.10	12.12	3.90	15.15	8.55	3.03	1.50	6.06	4.50	21.21	14.99
Rte. 50 & Jermantown Rd.	9.09	10.19	3.03	0.60	6.06	6.90	0.00	0.00	6.06	5.25	15.15	19.79
Rte. 29/50 & Plantation Pkwy	6.06	6.00	3.03	1.05	3.03	3.15	3.03	0.00	9.09	2.85	9.09	11.39
Rte. 236 & Pickett Rd.	3.03	16.64	0.00	1.95	3.03	9.60	0.00	0.75	3.03	9.90	6.06	29.24

Table B4. Fairfax City Comparison Site Crash Rates Normalized by Time (Crashes per Intersection Year)

Intersection	Rear-end		Red Light Running		Angle		Injury Red Light Running		Injury		Total	
	Before Camera	After Camera	Before Camera	After Camera	Before Camera	After Camera	Before Camera	After Camera	Before Camera	After Camera	Before Camera	After Camera
Main St. (236) & Burke Station Rd. (652)	6.00	9.60	0.00	0.75	0.00	3.90	0.00	0.45	3.00	5.10	6.00	14.10
Main St. (236) & Lee Hwy (29/50)	12.00	10.95	3.00	2.40	3.00	10.05	3.00	0.90	9.00	8.10	15.00	23.40
Lee Hwy (29/50) & Stafford Dr.	0.00	2.10	0.00	0.60	3.00	2.25	0.00	0.15	3.00	1.80	3.00	5.40

Table B5. Fairfax County Camera Site Crash Rates Normalized by Time (Crashes per Intersection Year)

Intersection	Rear-end		Red Light Running		Angle		Injury Red Light Running		Injury		Total	
	Before Camera	After Camera	Before Camera	After Camera	Before Camera	After Camera	Before Camera	After Camera	Before Camera	After Camera	Before Camera	After Camera
Arlington Blvd. & Jaguar Trail	8.70	11.45	3.60	1.36	8.11	7.63	1.80	0.82	7.81	7.63	18.32	21.53
Fairfax County Pkwy & Newington Rd.	0.00	0.00	0.27	0.00	0.53	0.00	0.00	0.00	0.00	0.00	0.53	0.00
Fairfax County Pkwy & Popes Head Rd.	2.57	6.86	0.29	0.00	3.43	3.14	0.29	0.00	3.43	6.00	6.57	11.43
Lee Jackson Hwy & Fair Ridge	16.56	17.60	4.55	1.79	6.82	3.06	3.57	1.02	10.06	8.16	26.30	22.70
Lee Jackson Hwy & Rugby/Middle Ridge	9.09	11.48	2.60	2.04	3.57	4.08	1.95	1.02	6.17	4.34	13.96	16.58
Leesburg Pike & Dranesville Rd.	11.71	14.86	2.29	3.14	3.71	4.86	1.43	2.29	5.71	10.57	15.71	22.29
Leesburg Pike & Route 66	9.31	7.36	2.40	2.72	3.00	3.81	0.90	1.63	4.50	5.18	13.21	12.26
Leesburg Pike & Towlston Rd.	2.18	7.06	0.73	0.24	1.09	1.65	0.73	0.00	2.18	4.00	5.09	9.65
Leesburg Pike & Westpark/Gosnell	12.62	15.93	3.15	1.57	14.51	19.06	1.58	0.52	11.36	11.23	29.02	38.38
Route 236 (Little River) & Heritage/Hummer	11.56	21.03	3.21	0.43	11.56	10.30	0.86	0.00	4.93	18.45	28.27	34.76
Route 28 (Centreville) & Green Trails/Old Mill	3.51	11.17	0.88	0.28	2.63	4.75	0.29	0.00	2.92	6.98	7.60	17.04
Route 7 & Carlin Springs	6.00	6.01	1.35	1.09	8.90	10.38	0.58	0.00	6.96	4.37	18.18	20.22
Telegraph & Huntington/95/495	12.96	24.04	7.35	4.92	26.89	25.68	3.29	2.19	17.79	22.40	43.33	53.45

Table B6. Fairfax County Comparison Site Crash Rates Normalized by Time (Crashes per Intersection Year)

Intersection	Rear-end		Red Light Running		Angle		Injury Red Light Running		Injury		Total	
	Before Camera	After Camera	Before Camera	After Camera	Before Camera	After Camera	Before Camera	After Camera	Before Camera	After Camera	Before Camera	After Camera
Braddock (620) & Kings Park	10.67	7.00	2.33	0.50	7.67	1.75	1.00	0.25	10.00	3.75	19.33	9.25
Braddock (620) & Port Royal	14.33	12.00	2.67	1.75	9.33	6.50	1.00	1.00	7.67	6.75	27.00	20.00
Braddock (620) & Queensbury	22.67	18.50	2.67	2.25	4.67	6.00	1.33	1.25	12.00	9.75	28.33	26.25
Braddock (620) & Southhampton	8.00	9.50	0.67	0.25	3.67	2.50	0.67	0.25	4.67	5.25	13.67	12.00
Braddock (620) & Wakefield Chapel	11.67	10.25	0.33	0.50	6.33	6.50	0.33	0.25	7.33	7.75	20.00	18.50
Chain Bridge (123) & Jermantown	4.67	4.00	0.33	1.50	6.00	7.00	0.00	0.50	4.67	5.00	12.67	13.75
Chain Bridge (123) & Old Courthouse	8.00	4.75	2.00	1.25	9.33	11.00	0.67	0.25	5.33	3.25	17.00	16.50
Dolley Madison Blvd. (123) & Old Chain Bridge Rd.	0.67	1.00	2.33	0.75	4.33	3.25	1.33	0.25	3.33	1.00	5.67	4.50
Dolley Madison Blvd. (123/309) & Old Dominion	8.67	8.50	0.00	0.50	2.67	4.25	0.00	0.00	5.00	4.00	14.00	14.25
Lawyers (644) & West Ox/ Folkstone	0.00	0.50	0.00	0.25	0.00	0.25	0.00	0.00	0.00	0.75	0.00	1.00
Lee Hwy (29) & Circle Woods	1.00	1.75	0.00	0.25	1.67	1.25	0.00	0.25	0.67	1.25	3.00	3.75
Lee Hwy (29) & Nutley	4.67	3.00	1.00	0.25	6.67	6.25	0.33	0.00	5.00	5.00	13.00	11.50
Nutley (243) & Hermosa Dr.	2.33	2.75	2.00	2.75	4.33	4.00	1.00	1.50	3.67	2.00	7.00	7.00
Nutley (243) & Swanee/ Metro So.	2.33	1.25	0.00	0.25	3.33	1.75	0.00	0.25	1.33	1.75	6.00	3.75
Old Keene Mill (644) & Greeley Blvd.	5.33	3.75	2.67	2.75	4.67	4.50	1.00	1.00	3.67	3.00	12.00	9.00
Old Keene Mill (644) & Hanover Ave.	5.67	7.00	3.00	1.00	6.33	6.00	1.33	0.25	3.67	7.25	14.33	15.00
Old Keene Mill (644) & Huntsman	5.33	3.25	0.33	0.50	5.33	6.25	0.00	0.25	4.00	3.25	12.00	10.25
Reston Pkwy (602) & Bluemont/Market	6.00	4.75	0.33	1.00	2.00	2.25	0.00	0.75	1.67	2.75	9.33	7.25
Reston Pkwy (602) & Bowmantown	1.00	1.75	1.33	1.25	3.67	3.25	0.00	0.50	1.00	2.25	5.33	5.75

Intersection	Rear-end		Red Light Running		Angle		Injury Red Light Running		Injury		Total	
	Before Camera	After Camera	Before Camera	After Camera	Before Camera	After Camera	Before Camera	After Camera	Before Camera	After Camera	Before Camera	After Camera
Reston Pkwy (602) & Sunset Hills	19.67	10.50	1.67	2.75	7.33	4.50	1.33	1.25	13.00	6.50	28.67	16.75
Reston Pkwy (602) & Temporary Rd./New Dominion	10.00	1.75	3.33	0.50	8.00	3.00	2.00	0.25	8.00	2.50	18.33	6.00
Sully Rd. (28) & Westfields Blvd.	12.67	17.75	3.67	2.00	6.33	4.50	2.67	1.25	10.67	12.00	20.33	25.00
Sully Rd. (28) & Braddock /Walney	13.00	26.50	1.33	2.25	3.00	8.25	0.67	2.00	5.67	14.00	16.67	39.00
Sully Rd. (28) & Willard	13.33	14.25	3.00	1.00	7.33	5.25	1.00	0.50	4.67	6.50	23.67	23.25
Van Dorn (613) & Crown Royal	4.33	3.75	0.33	0.50	1.33	1.00	0.33	0.25	2.33	2.25	7.33	5.75
Van Dorn (613) & Franconia	15.67	12.75	0.33	0.50	2.67	2.25	0.33	0.50	6.67	5.50	21.33	17.00
Van Dorn (613) & Oakwood	1.00	2.75	0.00	0.25	0.00	0.25	0.00	0.00	0.67	1.00	1.00	3.00
Van Dorn (613) & Woodfield/ Chrysanthemum	4.00	4.25	0.33	0.50	1.67	0.75	0.33	0.25	2.33	1.75	6.00	5.50
West Ox (608) & Fairlakes Pkwy	5.33	5.00	1.67	1.25	14.00	8.50	0.33	1.00	8.67	7.00	21.33	15.50
West Ox (608) & Monument Dr.	2.67	4.50	1.67	2.25	2.67	2.75	0.33	1.25	2.00	4.00	5.67	7.75
West Ox (608) & Piney Branch Rd./Transfer	2.00	2.00	0.00	0.75	2.67	2.75	0.00	0.00	1.67	0.75	5.00	5.00
West Ox (608) & Price Club Connector Rd.	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.25	0.00	0.25
West Ox (608) & Cedar Lakes /Hanger	0.67	0.50	1.33	0.25	2.00	0.75	1.00	0.00	1.33	0.25	2.67	1.25

Table B7. Falls Church Camera Site Crash Rates Normalized by Time (Crashes per Intersection Year)

Intersection	Rear-end		Red Light Running		Angle		Injury Red Light Running		Injury		Total	
	Before Camera	After Camera	Before Camera	After Camera	Before Camera	After Camera	Before Camera	After Camera	Before Camera	After Camera	Before Camera	After Camera
W. Broad St. (SR 7) & Annandale Rd.	1.87	1.85	0.80	1.23	1.60	1.26	0.27	0.92	0.53	1.85	5.07	3.38
W. Broad St. (SR 7) & Birch St.	1.15	3.75	0.00	0.75	3.46	2.62	0.00	0.37	1.62	4.87	5.54	8.61
W. Broad St. (SR7) & Cherry St.	2.15	0.00	1.23	0.00	2.46	0.00	0.77	0.00	2.46	0.00	5.38	0.00

Table B8. Falls Church Comparison Site Crash Rates Normalized by Time (Crashes per Intersection Year)

Intersection	Rear-end		Red Light Running		Angle		Injury Red Light Running		Injury		Total	
	Before Camera	After Camera	Before Camera	After Camera	Before Camera	After Camera	Before Camera	After Camera	Before Camera	After Camera	Before Camera	After Camera
E. Broad St. (SR7) & Roosevelt (6792)	4.80	4.62	4.27	2.46	8.00	5.23	1.87	0.92	5.33	4.62	14.13	11.38
W. Broad St. (SR7) & North West (6749)	2.67	1.54	0.80	0.31	2.13	2.15	0.53	0.00	1.87	2.77	5.87	5.54
W. Broad St. (SR7) & Little Falls (6797)	1.33	0.92	0.27	0.00	1.87	1.85	0.00	0.00	1.33	1.54	4.27	3.69

Table B9. Vienna Camera Site Crash Rates Normalized by Time (Crashes per Intersection Year)

Intersection	Rear-end		Red Light Running		Angle		Injury Red Light Running		Injury		Total	
	Before Camera	After Camera	Before Camera	After Camera	Before Camera	After Camera	Before Camera	After Camera	Before Camera	After Camera	Before Camera	After Camera
Maple Ave E. & Follin Lane	12.68	11.11	0.70	0.18	1.41	1.08	0.00	0.00	5.63	3.94	15.49	12.90
Maple Ave W. & Nutley St.	6.78	6.40	0.52	0.00	3.30	8.80	0.35	0.00	5.74	6.40	11.48	17.60
Maple Ave W. & Glyndon St.	3.91	3.33	1.72	0.00	5.00	1.67	0.63	0.00	2.97	1.67	9.84	5.00

Table B10. Vienna Comparison Site Crash Rates Normalized by Time (Crashes per Intersection Year)

Intersection	Rear-end		Red Light Running		Angle		Injury Red Light Running		Injury		Total	
	Before Camera	After Camera	Before Camera	After Camera	Before Camera	After Camera	Before Camera	After Camera	Before Camera	After Camera	Before Camera	After Camera
Maple Ave. & Lawyers St.	0.71	3.05	0.00	0.00	1.41	3.58	0.00	0.00	0.00	1.97	2.82	7.17
Maple Ave. & Center St.	4.24	3.23	2.12	0.00	7.06	4.48	0.00	0.00	2.12	1.79	11.29	8.78
Maple Ave. & East St.	3.53	4.48	0.71	1.08	4.24	2.87	0.71	0.18	3.53	3.05	8.47	8.24

Table B11. Spillover Site Crash Rates Normalized by Time (Crashes per Intersection Year)

Intersection	Rear-end		Red Light Running		Angle		Injury Red Light Running		Injury		Total	
	Before Camera	After Camera	Before Camera	After Camera	Before Camera	After Camera	Before Camera	After Camera	Before Camera	After Camera	Before Camera	After Camera
Lee Hwy (29/50) & Stafford Dr.	0.00	2.10	0.00	0.30	3.00	2.25	0.00	0.00	3.00	1.80	3.00	5.40
Lee Hwy (29/50) & McLean/Warwick	0.00	4.35	0.00	0.30	0.00	2.70	0.00	0.00	0.00	2.85	0.00	7.95
Lee Hwy (29/50) & University	3.00	4.35	0.00	0.45	3.00	5.85	0.00	0.15	3.00	4.05	3.00	11.55
Leesburg Pike (SR 7) & FR 773	2.53	2.61	0.63	0.26	2.53	1.57	0.00	0.00	1.58	1.83	5.37	5.22
Leesburg Pike (SR 7) & Spring Hill	8.84	6.26	0.32	1.04	13.26	12.52	0.32	0.52	7.26	4.96	23.37	19.57
E. Broad St. (SR 7) & Roosevelt (6792)	4.62	6.00	2.46	2.00	6.31	10.00	1.38	2.00	5.33	4.62	13.23	8.00
W. Broad St. (SR 7) & North West (6749)	2.54	1.50	0.69	0.37	2.54	1.50	0.46	0.00	1.87	2.77	6.24	4.87
W. Broad St. (SR 7) & Little Falls (6797)	1.07	1.23	0.27	0.00	1.87	1.54	0.00	0.00	1.33	1.54	4.27	3.69
Broad St. (SR 7) & Haycock (703)	2.77	2.62	0.92	0.75	6.00	3.37	0.46	0.00	3.70	2.62	9.93	7.49
Broad St. (SR 7) & Virginia Ave.	2.67	2.15	0.00	0.92	1.33	0.31	0.00	0.00	1.87	1.54	4.80	4.92
Broad St. (SR 7) & Washington Ave.	4.62	8.00	1.08	2.00	6.62	10.00	0.92	2.00	6.46	10.00	14.15	16.00
Maple Ave. (SR 123) & Branch Rd.	1.42	1.49	0.16	0.00	2.21	1.49	0.00	0.00	1.11	1.49	4.11	3.00
Maple Ave. (SR 123) & Park St.	4.11	5.97	0.32	0.00	6.16	7.46	0.16	0.00	3.16	1.49	11.53	14.93
Chainbridge Rd. (123) & Flint Hill	3.83	3.20	0.17	0.00	0.87	1.60	0.00	0.00	2.09	0.80	5.57	4.80
Maple Ave. & Lawyers St.	1.22	8.80	0.00	0.00	2.61	4.80	0.00	0.00	1.22	3.20	4.52	14.40

Table B12. All Jurisdictions: Camera Site Crash Rates Normalized by Time (Crashes per Intersection Year)[a]

Jurisdiction (Sites) [b]	Rear-end		Red Light Running		Angle		Injury Red Light Running		Injury		Total	
	Before	After	Before	After	Before	After	Before	After	Before	After	Before	After
Alexandria (1)	14.59	16.87	0.97	0.00	2.27	1.20	0.49	0.00	8.10	6.02	18.64	24.10
Arlington (4)	20.61	28.52	10.50	14.53	23.37	27.71	5.67	7.63	26.75	33.97	53.22	67.70
Fairfax City (5)	33.33	52.02	24.24	15.45	36.36	40.79	6.06	3.75	33.27	32.69	75.75	105.40
Fairfax County (13)	106.78	154.84	32.66	19.58	94.76	98.41	17.26	9.49	83.83	109.32	226.10	280.39
Falls Church (3)	5.17	5.60	2.03	1.98	7.52	3.88	1.04	1.29	4.61	6.72	15.99	11.99
Vienna (3)	23.36	20.84	2.94	0.18	9.71	11.54	0.97	0.00	14.34	12.01	36.81	35.50
Total (29)	203.84	278.69	73.34	51.72	176.26	183.53	31.49	22.16	170.90	200.73	426.51	525.08
Percent Change	37%		-29%		4%		-30%		17%		23%	

[a]Results generated by summing Tables B1, B3, B5, B7, and B9 plus the single camera site (with before/after data) from Alexandria
[b]Denotes number of camera intersections with before and after data

APPENDIX C

IMPACT OF CAMERAS ON CRASHES, NORMALIZED BY TIME AND TOTAL ADT

Table C1. Arlington Camera Site Crash Rates Normalized by Time and Total ADT (Crashes per Intersection Year per Million Entering Vehicles)[a]

Intersection	Rear-end		Red Light Running		Angle		Injury to Red Light Running		Injury		Total	
	Before Camera	After Camera	Before Camera	After Camera	Before Camera	After Camera	Before Camera	After Camera	Before Camera	After Camera	Before Camera	After Camera
Route 50 & Fillmore St.	93.0	142.3	30.9	27.0	77.4	63.7	15.6	12.2	139.3	115.3	247.6	242.7[a]
Route 50 & Manchester St.	157.3	185.1	45.0	41.3	98.9	111.2	22.5	33.0	125.8	185.5	269.6	321.5
Wilson Blvd. & Lynn St.	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Lynn St. & Lee Hwy	47.4	40.7	110.6	166.9	205.2	248.5	63.2	73.3	150.0	171.0	308.0	407.2
Route 1 & 27th St.	112.8	119.5	0.0	27.7	75.0	73.8	0.0	18.4	112.7	128.9	225.9	221.0

[a]Rates in Appendix C are defined as crashes per million ADT per intersection-year, where ADT was the number of entering vehicles on a single day and intersection-years was the length of the period. For example, at the intersection of Route 50 & Fillmore Street, the camera was installed in February 1999. Thus there were 1,08 before intersection years (January 1, 1998 through January 31, 1999) and 5.92 after intersection years (February 1, 1999 through December 31, 2004). During the after period, the weighted total average daily traffic (ADT) was 68,894 and 99 total crashes were observed. The after-camera total crash rate for this intersection was thus (99 X 1 million) /(68,894 ADT X 5.92 intersection years) = 242.7 as shown in the far right column and top row of Table C1.

Table C2. Arlington Comparison Site Crash Rates Normalized by Time and Total ADT (Crashes per Intersection Year per Million Entering Vehicles)

Intersection	Rear-end		Red Light Running		Angle		Injury Red Light Running		Injury		Total	
	Before Camera	After Camera	Before Camera	After Camera	Before Camera	After Camera	Before Camera	After Camera	Before Camera	After Camera	Before Camera	After Camera
Route 50 & Pershing Dr.	93.3	35.7	31.1	20.4	155.5	74.0	0.0	10.2	155.5	76.6	264.4	143.0
Wilson Blvd. & George Mason Dr.	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Columbia Pike (244) & Walter Reed Dr.	38.3	60.1	0.0	18.8	57.4	82.7	0.0	0.0	114.9	78.9	172.3	225.5

Table C3. Fairfax City Camera Site Crash Rates Normalized by Time and Total ADT (Crashes per Intersection Year per Million Entering Vehicles)

Intersection	Rear-end		Red Light Running		Angle		Injury Red Light Running		Injury		Total	
	Before Camera	After Camera	Before Camera	After Camera	Before Camera	After Camera	Before Camera	After Camera	Before Camera	After Camera	Before Camera	After Camera
Rt. 50 & Lee Hwy/Old Lee Hwy & Fairfax Circle	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Rte. 123 & Eaton Place	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Rte. 29/50 & Rte. 123	199.3	219.0	99.7	39.6	149.5	195.6	0.0	23.3	149.5	158.3	398.7	466.0
Rte. 123 & North St.	90.3	135.9	361.3	103.9	451.6	227.8	90.3	40.0	180.6	119.9	632.2	399.3
Rte. 50 & Jermantown Rd.	117.7	142.6	39.2	8.4	78.5	96.6	0.0	0.0	78.5	73.5	196.1	277.0
Rte. 29/50 & Plantation Pkwy	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Rte. 236 & Pickett Rd.	30.4	197.4	0.0	23.1	30.4	113.9	0.0	8.9	30.4	117.5	60.8	346.9

Table C4. Fairfax City Comparison Site Crash Rates Normalized by Time and Total ADT (Crashes per Intersection Year per Million Entering Vehicles)

Intersection	Rear-end		Red Light Running		Angle		Injury Red Light Running		Injury		Total	
	Before Camera	After Camera	Before Camera	After Camera	Before Camera	After Camera	Before Camera	After Camera	Before Camera	After Camera	Before Camera	After Camera
Main St. (236) & Burke Station Rd. (652)	107.7	196.9	0.0	15.4	0.0	80.0	0.0	9.2	53.9	104.6	107.7	289.2
Main St. (236) & Lee Hwy (29/50)	158.9	152.7	39.7	33.5	39.7	140.1	39.7	12.6	119.2	113.0	198.7	326.3
Lee Hwy (29/50) & Stafford Dr.	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Table C5. Fairfax County Camera Site Crash Rates Normalized by Time and Total ADT (Crashes per Intersection Year per Million Entering Vehicles)

Intersection	Rear-end		Red Light Running		Angle		Injury Red Light Running		Injury		Total	
	Before Camera	After Camera	Before Camera	After Camera	Before Camera	After Camera	Before Camera	After Camera	Before Camera	After Camera	Before Camera	After Camera
Arlington Blvd. & Jaguar Trail	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Fairfax County Pkwy & Newington Rd.	0.0	0.0	7.3	0.0	14.6	0.0	0.0	0.0	0.0	0.0	14.6	0.0
Fairfax County Pkwy & Popes Head Rd.	52.2	117.0	5.8	0.0	69.6	53.6	5.8	0.0	69.6	102.4	133.3	195.0
Lee Jackson Hwy & Fair Ridge	228.0	225.0	62.6	22.8	93.9	39.1	49.2	13.0	138.6	104.4	362.1	290.2
Lee Jackson Hwy & Rugby/Middle Ridge	144.8	153.8	41.4	27.3	56.9	54.7	31.0	13.7	98.3	58.1	222.4	222.1
Leesburg Pike & Dranesville Rd.	233.5	259.2	45.7	54.8	74.0	84.8	28.5	39.9	113.9	184.4	313.2	388.8
Leesburg Pike & Route 66	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Leesburg Pike & Towlston Rd.	40.0	131.4	13.3	4.4	20.0	30.7	13.3	0.0	40.0	74.4	93.2	179.5
Leesburg Pike & Westpark/Gosnell	181.4	189.5	45.3	18.6	208.6	226.8	22.7	6.2	163.2	133.6	417.1	456.7
Route 236 (Little River) & Heritage/Hummer	211.6	365.3	58.8	7.5	211.6	178.9	15.7	0.0	90.11	320.5	517.2	603.8
Route 28 (Centreville) & Green Trails/Old Mill	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Route 7 & Carlin Springs	109.9	105.8	24.8	19.2	163.1	182.7	10.6	0.0	127.7	76.9	333.4	355.7
Telegraph & Huntington/95/495	261.5	476.5	148.3	97.5	542.5	509.0	66.4	43.3	359.1	444.0	874.3	1061.3

Table C6. Fairfax County Comparison Site Crash Rates Normalized by Time and Total ADT (Crashes per Intersection Year per Million Entering Vehicles)

Intersection	Rear-end		Red Light Running		Angle		Injury Red Light Running		Injury		Total	
	Before Camera	After Camera	Before Camera	After Camera	Before Camera	After Camera	Before Camera	After Camera	Before Camera	After Camera	Before Camera	After Camera
Braddock (620) & Kings Park	165.7	99.7	36.2	7.1	119.1	24.9	15.5	3.6	155.3	53.4	300.2	131.7
Braddock (620) & Port Royal	199.6	131.7	37.1	19.2	130.0	71.3	13.9	11.0	106.8	74.1	376.0	219.5
Braddock (620) & Queensbury	309.1	235.1	36.4	28.6	63.6	76.2	18.2	15.9	163.6	123.9	386.3	333.5
Braddock (620) & Southhampton	127.8	137.9	10.7	3.6	58.6	36.3	10.7	3.6	74.6	76.2	218.3	174.2
Braddock (620) & Wakefield Chapel	178.4	120.2	5.1	5.9	96.8	76.2	5.1	2.9	112.1	90.9	305.8	217.0
Chain Bridge (123) & Jermantown	74.6	77.8	5.3	29.2	95.9	136.2	0.0	9.7	74.6	97.3	202.4	267.5
Chain Bridge (123) & Old Courthouse	156.5	116.1	39.1	30.5	182.6	268.8	13.0	6.1	104.3	79.4	332.6	403.2
Dolley Madison Blvd. (123) & Old Chain Bridge Rd.	17.0	26.0	59.4	19.5	110.3	84.4	34.0	6.5	84.9	26.0	144.3	116.9
Dolley Madison Blvd. (123/309) & Old Dominion	150.5	165.9	0.0	9.8	46.3	83.0	0.0	0.0	86.8	78.1	243.2	278.1
Lawyers (644) & West Ox/ Folkstone	0.0	15.6	0.0	7.8	0.0	7.8	0.0	0.0	0.0	23.3	0.0	31.1
Lee Hwy (29) & Circle Woods	18.9	40.3	0.0	5.8	31.5	28.8	0.0	5.8	12.6	28.8	56.7	86.3
Lee Hwy (29) & Nutley	67.1	41.4	14.4	3.5	95.8	86.4	4.8	0.0	71.9	69.1	186.8	158.9
Nutley (243) & Hermosa Dr.	63.2	80.5	54.1	80.5	117.3	117.1	27.1	43.9	99.2	58.6	189.5	205.0
Nutley (243) & Swanee/ Metro So.	64.4	37.3	0.0	7.5	91.9	52.3	0.0	7.5	36.8	52.3	165.5	112.0
Old Keene Mill (644) & Greeley Blvd.	141.1	87.1	70.5	63.9	123.5	104.6	26.5	23.2	97.0	69.7	317.5	209.1
Old Keene Mill (644) & Hanover Ave.	114.9	130.2	60.8	18.6	128.4	111.6	27.0	4.7	74.3	134.9	290.5	279.1
Old Keene Mill (644) & Huntsman	107.1	73.2	6.7	11.3	107.1	140.7	0.0	5.6	80.3	73.2	240.9	230.8
Reston Pkwy (602) & Bluemont/Market	140.6	93.5	7.8	19.7	46.9	44.3	0.0	14.8	39.1	54.2	218.7	142.8
Reston Pkwy (602) & Bowmantown	24.9	37.5	33.2	26.8	91.2	69.7	0.0	10.7	24.9	48.3	132.6	123.3

Intersection	Rear-end		Red Light Running		Angle		Injury Red Light Running		Injury		Total	
	Before Camera	After Camera	Before Camera	After Camera	Before Camera	After Camera	Before Camera	After Camera	Before Camera	After Camera	Before Camera	After Camera
Reston Pkwy (602) & Sunset Hills	363.2	167.2	30.8	43.8	135.4	71.6	24.6	19.9	240.1	103.5	529.4	266.7
Reston Pkwy (602) & Temporary Rd./New Dominion	211.4	32.5	70.5	9.3	169.1	55.7	42.3	4.6	169.1	46.5	387.4	111.5
Sully Rd. (28) & Westfields Blvd.	174.8	206.1	50.6	23.2	87.4	52.3	36.8	14.5	147.2	139.3	280.6	290.3
Sully Rd. (28) & Braddock/ Walney	184.3	321.7	18.9	27.3	42.5	100.2	9.5	24.3	80.4	170.0	236.3	473.5
Sully Rd. (28) & Willard	191.7	173.5	43.1	12.2	105.5	63.9	14.4	6.1	67.1	79.2	340.3	283.1
Van Dorn (613) & Crown Royal	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Van Dorn (613) & Franconia	191.2	142.5	4.1	5.6	32.6	25.2	4.1	5.6	81.4	61.5	260.4	190.0
Van Dorn (613) & Oakwood	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Van Dorn (613) & Woodfield/ Chrysanthemum	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
West Ox (608) & Fairlakes Pkwy	104.1	93.3	32.5	23.3	273.2	158.6	6.5	18.7	169.1	130.6	416.2	289.2
West Ox (608) & Monument Dr.	68.3	125.1	42.7	62.5	68.3	76.4	8.5	34.7	51.2	111.2	145.1	215.4
West Ox (608) & Piney Branch Rd./Transfer	60.8	58.3	0.0	21.9	81.1	80.1	0.0	0.0	50.7	21.9	152.1	145.7
West Ox (608) & Price Club Connector Rd.	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	7.3	0.0	7.3
West Ox (608) & Cedar Lakes/ Hanger	23.0	17.5	46.0	8.8	69.0	26.3	34.5	0.0	46.0	8.8	92.0	43.8

Table C7. Falls Church Camera Site Crash Rates Normalized by Time and Total ADT (Crashes per Intersection Year per Million Entering Vehicles)

Intersection	Rear-end		Red Light Running		Angle		Injury Red Light Running		Injury		Total	
	Before Camera	After Camera	Before Camera	After Camera	Before Camera	After Camera	Before Camera	After Camera	Before Camera	After Camera	Before Camera	After Camera
W. Broad St. (SR 7) & Annandale Rd.	52.9	57.5	22.6	38.2	45.3	39.2	7.6	28.6	15.0	57.5	143.4	105.1
W. Broad St. (SR 7) & Birch St.	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
W. Broad St. (SR7) & Cherry St.	77.5	0.0	44.4	0.0	88.7	0.0	27.8	0.0	88.7	0.0	194.0	0.0

Table C8. Falls Church Comparison Site Crash Rates Normalized by Time and Total ADT (Crashes per Intersection Year per Million Entering Vehicles)

Intersection	Rear-end		Red Light Running		Angle		Injury Red Light Running		Injury		Total	
	Before Camera	After Camera	Before Camera	After Camera	Before Camera	After Camera	Before Camera	After Camera	Before Camera	After Camera	Before Camera	After Camera
E. Broad St. (SR7) & Roosevelt (6792)	150.6	175.4	134.0	93.4	251.0	198.5	58.7	34.9	167.3	175.4	443.5	432.1
W. Broad St. (SR7) & North West (6749)	94.4	43.1	28.3	8.7	75.4	60.3	18.7	0.0	66.1	77.6	207.5	155.1
W. Broad St. (SR7) & Little Falls (6797)	39.7	30.8	8.0	0.0	55.7	61.8	0.0	0.0	39.7	51.5	127.2	123.6

Table C9. Vienna Camera Site Crash Rates Normalized by Time and Total ADT (Crashes per Intersection Year per Million Entering Vehicles)

Intersection	Rear-end		Red Light Running		Angle		Injury Red Light Running		Injury		Total	
	Before Camera	After Camera	Before Camera	After Camera	Before Camera	After Camera	Before Camera	After Camera	Before Camera	After Camera	Before Camera	After Camera
Maple Ave E. & Follin Lane	309.4	278.0	17.1	4.5	34.4	27.0	0.0	0.0	137.4	98.6	378.0	322.8
Maple Ave W. & Nutley St.	107.6	91.1	8.3	0.0	52.4	125.2	5.6	0.0	91.1	91.1	182.2	250.5
Maple Ave W. & Glyndon St.	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Table C10. Vienna Comparison Site Crash Rates Normalized by Time and Total ADT (Crashes per Intersection Year per Million Entering Vehicles)

Intersection	Rear-end		Red Light Running		Angle		Injury Red Light Running		Injury		Total	
	Before Camera	After Camera	Before Camera	After Camera	Before Camera	After Camera	Before Camera	After Camera	Before Camera	After Camera	Before Camera	After Camera
Maple Ave. & Lawyers St.	14.4	63.4	0.0	0.0	28.8	74.5	0.0	0.0	0.0	41.0	57.6	149.1
Maple Ave. & Center St.	107.2	82.4	53.6	0.0	178.6	114.4	0.0	0.0	53.6	45.8	285.8	224.3
Maple Ave. & East St.	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Table C11. Spillover Site Crash Rates Normalized by Time and Total ADT (Crashes per Intersection Year per Million Entering Vehicles)

Intersection	Rear-end		Red Light Running		Angle		Injury Red Light Running		Injury		Total	
	Before Camera	After Camera	Before Camera	After Camera	Before Camera	After Camera	Before Camera	After Camera	Before Camera	After Camera	Before Camera	After Camera
Lee Hwy (29/50) & Stafford Dr.	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Lee Hwy (29/50) & McLean/Warwick	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Lee Hwy (29/50) & University	75.42	100.97	0.00	10.45	75.42	135.79	0.00	3.48	75.42	94.01	75.42	268.09
Leesburg Pike (SR 7) & FR 773	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Leesburg Pike (SR 7) & Spring Hill	150.18	88.04	5.36	14.67	225.27	176.07	5.36	7.34	123.36	69.70	396.91	275.11
E. Broad St. (SR 7) & Roosevelt (6792)	156.19	229.89	83.30	76.63	213.46	383.14	46.86	76.63	180.37	177.01	447.74	306.51
W. Broad St. (SR 7) & North West (6749)	88.46	40.93	24.13	10.23	88.46	40.93	16.08	0.00	65.12	75.68	217.14	133.02
W. Broad St. (SR 7) & Little Falls (6797)	31.80	41.20	7.95	0.00	55.65	51.49	0.00	0.00	39.65	51.55	127.21	123.59
Broad St. (SR 7) & Haycock (703)	85.19	52.31	28.40	14.95	184.59	67.26	14.20	0.00	113.59	52.31	305.28	149.46
Broad St. (SR 7) & Virginia Ave.	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Broad St. (SR 7) & Washington Ave.	83.06	153.85	19.38	38.46	119.05	192.31	16.61	38.46	116.29	192.31	254.72	307.69
Maple Ave. (SR 123) & Branch Rd.	37.26	34.63	4.14	0.00	57.96	34.63	0.00	0.00	28.98	34.63	107.59	69.61
Maple Ave. (SR 123) & Park St.	93.26	121.84	7.17	0.00	139.89	152.30	3.59	0.00	71.74	30.46	261.85	304.60
Chainbridge Rd. (123) & Flint Hill	109.11	84.46	4.84	0.00	24.78	42.23	0.00	0.00	59.54	21.11	158.68	126.68
Maple Ave. & Lawyers St.	25.59	172.49	0.00	0.00	54.75	94.09	0.00	0.00	25.59	62.72	94.81	282.26

Table C12. All Jurisdictions: Camera Site Crash Rates Normalized by Time and Total ADT (Crashes per Intersection Year per Million Entering Vehicles)[a]

Jurisdiction (Sites) [b]	Rear-end		Red Light Running		Angle		Injury Red Light Running		Injury		Total	
	Before	**After**	**Before**	**After**	**Before**	**After**	**Before**	**After**	**Before**	**After**	**Before**	**After**
Alexandria (1)	418.98	535.56	27.86	0.00	65.19	38.10	14.07	0.00	232.61	191.11	535.24	764.96
Arlington (4)	410.37	487.47	186.55	262.89	456.56	497.14	101.29	136.89	527.82	600.63	1051.11	1192.35
Fairfax City (4)	437.71	694.86	500.15	175.05	709.90	633.88	90.31	72.17	438.96	469.16	1287.75	1489.25
Fairfax County (10)	1462.75	2023.29	453.28	252.09	1454.65	1360.17	243.16	116.18	1200.27	1498.62	3280.76	3753.04
Falls Church (2)	130.41	57.52	66.98	38.24	133.95	39.18	35.40	28.60	103.69	57.52	337.39	105.09
Vienna (2)	417.01	369.07	25.33	4.50	86.78	152.26	5.56	0.00	228.48	189.66	560.18	573.25
Total (23)	3277.23	4167.77	1260.15	732.77	2907.03	2720.73	489.79	353.84	2731.83	3006.70	7052.43	7877.94
Percent Change	27%		-42%		-6%		-28%		10%		12%	

[a]Results generated by summing Tables C1, C3, C5, C7, and C9 plus the single camera site (with before/after data) from Alexandria.
[b]Denotes number of camera intersections with before and after data.

APPENDIX D

PAIRED *t*-TEST RESULTS, NORMALIZED BY TIME

Table D1. Results of *t*-Tests for Arlington

Site	Crash Type	Change	*p*-Value
Camera Sites	Rear-end	Nonsignificant increase	0.139
	Red Light Running	Nonsignificant increase	0.269
	Angle	Nonsignificant increase	0.170
	Injury Red Light Running	Nonsignificant increase	0.095
	Total Injury	Nonsignificant increase	0.199
	Total	Significant increase	0.041
Comparison Sites	Rear-end	Nonsignificant decrease	0.668
	Red Light Running	Nonsignificant increase	0.837
	Angle	Nonsignificant decrease	0.637
	Injury Red Light Running	Nonsignificant increase	0.500
	Total Injury	Nonsignificant decrease	0.216
	Total	Nonsignificant decrease	0.682

Table D2. Results of *t*-Tests for Fairfax City

Site	Crash Type	Change	*p*-Value
Camera Sites	Rear-end	Nonsignificant increase	0.209
	Red Light Running	Nonsignificant decrease	0.157
	Angle	Nonsignificant increase	0.706
	Injury Red Light Running	Nonsignificant decrease	0.601
	Total Injury	Nonsignificant decrease	0.955
	Total	Nonsignificant increase	0.284
Comparison Sites	Rear-end	Nonsignificant increase	0.375
	Red Light Running	Nonsignificant increase	0.618
	Angle	Nonsignificant increase	0.272
	Injury Red Light Running	Nonsignificant decrease	0.598
	Total Injury	Nonsignificant increase	1.000
	Total	Nonsignificant increase	0.084

Table D3. Results of *t*-Tests for Fairfax County

Site	Crash Type	Change	*p*-Value
Camera Sites	Rear-end	Significant increase	0.004
	Red Light Running	Significant decrease	0.011
	Angle	Nonsignificant increase	0.616
	Injury Red Light Running	Significant decrease	0.029
	Total Injury	Nonsignificant increase	0.124
	Total	Significant increase	0.004
Comparison Sites	Rear-end	Nonsignificant increase	0.461
	Red Light Running	Nonsignificant increase	0.153
	Angle	Nonsignificant decrease	0.081
	Injury Red Light Running	Nonsignificant decrease	0.423
	Total Injury	Nonsignificant increase	0.429
	Total	Nonsignificant increase	0.259

Table D4. Results of *t*-Tests for Falls Church

Site	Crash Type	Change	*p*-Value
Camera Sites	Rear-end	Nonsignificant increase	0.926
	Red Light Running	Nonsignificant decrease	0.981
	Angle	Nonsignificant decrease	0.198
	Injury Red Light Running	Nonsignificant increase	0.866
	Total Injury	Nonsignificant increase	0.716
	Total	Nonsignificant decrease	0.640
Comparison Sites	Rear-end	Nonsignificant decrease	0.181
	Red Light Running	Nonsignificant decrease	0.217
	Angle	Nonsignificant decrease	0.423
	Injury Red Light Running	Nonsignificant decrease	0.213
	Total Injury	Nonsignificant increase	0.808
	Total	Nonsignificant decrease	0.254

Table D5. Results of *t*-Tests for Vienna

Site	Crash Type	Change	*p*-Value
Camera Sites	Rear-end	Nonsignificant decrease	0.149
	Red Light Running	Nonsignificant decrease	0.148
	Angle	Nonsignificant increase	0.835
	Injury Red Light Running	Nonsignificant decrease	0.215
	Total Injury	Nonsignificant decrease	0.397
	Total	Nonsignificant decrease	0.908
Comparison Sites	Rear-end	Nonsignificant increase	0.516
	Red Light Running	Nonsignificant decrease	0.530
	Angle	Nonsignificant decrease	0.719
	Injury Red Light Running	Nonsignificant decrease	0.423
	Total Injury	Nonsignificant increase	0.673
	Total	Nonsignificant increase	0.816

Table D6. Results of *t*-Tests for Spillover Sites

Crash Type	Change	*p*-Value
Rear-end	Nonsignificant increase	0.065
Red Light Running	Nonsignificant increase	0.466
Angle	Nonsignificant increase	0.276
Injury Red Light Running	Nonsignificant increase	0.519
Total Injury	Nonsignificant increase	0.463
Total	Nonsignificant increase	0.301

APPENDIX E

PAIRED *t*-TEST RESULTS, NORMALIZED BY TIME AND TOTAL ADT

Table E1. Results of *t*-Tests for Arlington

Site	Crash Type	Change	*p*-Value
Camera Sites	Rear-end	Nonsignificant increase	0.214
	Red Light Running	Nonsignificant increase	0.279
	Angle	Nonsignificant increase	0.468
	Injury Red Light Running	Nonsignificant increase	0.143
	Total Injury	Nonsignificant increase	0.365
	Total	Nonsignificant increase	0.255
Comparison Sites	Rear-end	Nonsignificant decrease	0.731
	Red Light Running	Nonsignificant increase	0.829
	Angle	Nonsignificant decrease	0.691
	Injury Red Light Running	Nonsignificant increase	0.500
	Total Injury	Nonsignificant decrease	0.228
	Total	Nonsignificant decrease	0.763

Table E2. Results of *t*-Tests for Fairfax City

Site	Crash Type	Change	*p*-Value
Camera Sites	Rear-end	Nonsignificant increase	0.161
	Red Light Running	Nonsignificant decrease	0.276
	Angle	Nonsignificant increase	0.802
	Injury Red Light Running	Nonsignificant decrease	0.795
	Total Injury	Nonsignificant increase	0.820
	Total	Nonsignificant increase	0.670
Comparison Sites	Rear-end	Nonsignificant increase	0.544
	Red Light Running	Nonsignificant increase	0.746
	Angle	Nonsignificant increase	0.072
	Injury Red Light Running	Nonsignificant decrease	0.708
	Total Injury	Nonsignificant increase	0.578
	Total	Nonsignificant increase	0.110

Table E3. Results of *t*-Tests for Fairfax County

Site	Crash Type	Change	*p*-Value
Camera Sites	Rear-end	Significant increase	0.044
	Red Light Running	Significant decrease	0.014
	Angle	Nonsignificant decrease	0.266
	Injury Red Light Running	Significant decrease	0.012
	Total Injury	Nonsignificant increase	0.295
	Total	Nonsignificant increase	0.063
Comparison Sites	Rear-end	Nonsignificant decrease	0.085
	Red Light Running	Nonsignificant decrease	0.140
	Angle	Nonsignificant decrease	0.068
	Injury Red Light Running	Nonsignificant decrease	0.379
	Total Injury	Nonsignificant decrease	0.139
	Total	Nonsignificant decrease	0.053

Table E4. Results of *t*-Tests for Falls Church

Site	Crash Type	Change	*p*-Value
Camera Sites	Rear-end	Nonsignificant decrease	0.538
	Red Light Running	Nonsignificant decrease	0.716
	Angle	Nonsignificant decrease	0.456
	Injury Red Light Running	Nonsignificant decrease	0.912
	Total Injury	Nonsignificant decrease	0.785
	Total	Nonsignificant decrease	0.376
Comparison Sites	Rear-end	Nonsignificant decrease	0.645
	Red Light Running	Nonsignificant decrease	0.140
	Angle	Nonsignificant decrease	0.354
	Injury Red Light Running	Nonsignificant decrease	0.189
	Total Injury	Significant increase	0.013
	Total	Nonsignificant decrease	0.276

Table E5. Results of *t*-Tests for Vienna

Site	Crash Type	Change	*p*-Value
Camera Sites	Rear-end	Nonsignificant decrease	0.192
	Red Light Running	Nonsignificant decrease	0.130
	Angle	Nonsignificant increase	0.564
	Injury Red Light Running	Nonsignificant decrease	0.500
	Total Injury	Nonsignificant decrease	0.500
	Total	Nonsignificant increase	0.933
Comparison Sites	Rear-end	Nonsignificant increase	0.798
	Red Light Running	Nonsignificant decrease	0.500
	Angle	Nonsignificant decrease	0.894
	Injury Red Light Running	N/A	N/A
	Total Injury	Nonsignificant increase	0.620
	Total	Nonsignificant increase	0.877

Table E6. Results of *t*-Tests for Spillover Sites

Crash Type	Change	*p*-Value
Rear-end	Nonsignificant increase	0.388
Red Light Running	Nonsignificant decrease	0.591
Angle	Nonsignificant increase	0.613
Injury Red Light Running	Nonsignificant increase	0.614
Total Injury	Nonsignificant decrease	0.789
Total	Nonsignificant decrease	0.806

APPENDIX F

ANOVA RESULTS BY JURISDICTION

In the ANOVA with a site identifier, the significance threshold was 0.10. (Thus, *p*-values greater than 0.10 were deemed nonsignificant, and *p*-values of 0.10 or less were deemed significant.) In the ANOVA with geometric data, for the smaller jurisdictions (Arlington, Fairfax City, Falls Church, and Vienna) the significance threshold was also 0.10. For the large jurisdictions (Fairfax County and All Jurisdictions) a significance threshold was 0.05.

The second ANOVA could not be performed for Vienna; the significance values of the variables could not be calculated because of the small size of the jurisdiction.

Table F1. Results of ANOVA with a Site Identifier for Arlington

Crash Type	Main or Second-order Effects	*p*-Value	Adjusted R^2
Rear-end Crashes	Site Identifier	0.000	0.700
	Total ADT	0.066	
Red Light Running Crashes	Site Identifier	0.000	0.686
Angle Crashes	Site Identifier	0.002	0.573
Injury Red Light Running Crashes	Site Identifier	0.011	0.432
Injury Crashes	Camera	0.094	0.398
	Total ADT * Truck	0.090	
All Crashes	No significant variables	---	0.478

Table F2. Results of ANOVA with Geometric Data for Arlington

Crash Type	Main or Second-order Effects	*p*-Value	Adjusted R^2
Rear-end Crashes	Total ADT	0.097	0.435
	Left-turn Lanes	0.001	
	Camera	0.058	
	Left-turn Lanes	0.000	
	Camera * Left-turn Lanes	0.078	
Angle Crashes	Left-turn Lanes	0.000	0.594
Injury Red Light Running	Left-turn Lanes	0.001	0.452
Injury Crashes	Total ADT * Truck Percent	0.046	0.332
All Crashes	No significant variables	---	0.375

Table F3. Results of ANOVA with a Site Identifier for Fairfax City

Crash Type	Main or Second-order Effects	*p*-Value	Adjusted R^2
Rear-end Crashes	Truck Percentage	0.048	0.329
Red Light Running Crashes	Site Identifier	0.079	0.589
	No significant variable	---	0.224
Injury Red Light Running Crashes	Site Identifier	0.078	0.309
	Total ADT	0.048	
	Total ADT	---	0.179
All Crashes	Truck Percentage	---	0.422

Table F4. Results of ANOVA with Geometric Data for Fairfax City

Crash Type	Main or Second-order Effects	*p*-Value	Adjusted R^2
Rear-end Crashes	Truck Percentage	0.032	0.321
Red Light Running Crashes	Left-turn Lanes	0.098	0.574
Angle Crashes	Left-turn Lanes	0.099	0.192
Injury Red Light Running Crashes	Total ADT	0.090	0.306
	Design Speed	---	0.180
All Crashes	Truck Percentage	---	0.412
	Left-turn Lanes	0.067	

Table F5. Results of ANOVA with a Site Identifier for Fairfax County

Crash Type	Main or Second-order Effects	*p*-Value	Adjusted R^2
Rear-end Crashes	Site Identifier	0.000	0.757
	Truck Percentage	0.081	
	Site Identifier	0.000	0.388
	Site Identifier	0.000	0.749
Red Light Running Crashes	Site Identifier	0.000	0.316
	Camera * ITE Difference	0.027	
Angle Crashes	Site Identifier	0.000	0.655
All Crashes	Site Identifier	0.000	0.777

Table F6. Results of ANOVA with Geometric Data for Fairfax County

Crash Type	Main or Second-order Effects	*p*-Value	Adjusted R^2
Rear-end Crashes	Truck Percent	0.005	0.638
	Total ADT * T Intersection	0.003	
	Total ADT	0.026	0.175
	Through Lanes	0.002	
	Left-turn Lanes	0.008	
	Camera * Curb Cuts	0.048	
	Total ADT * Through Lanes	0.005	
	Total ADT * Left-turn Lanes	0.017	
	Total ADT * Speed Limit	0.010	
	Truck Percent * Frontage	0.018	
Angle Crashes	Total ADT * Curb Cuts	0.025	0.594
	Truck Percent * Frontage	0.015	
	Frontage * Speed Limit	0.001	
	Curb Cuts * Speed Limit	0.048	
Injury Red Light Running Crashes	No significant variables	---	0.213
Injury Crashes	Camera	0.014	0.560
	Total ADT	0.036	
	Frontage	0.031	
	Through Lanes	0.045	
	Left-turn Lanes	0.001	
	Grade	0.014	
	Camera * Curb Cuts	0.006	
	Total ADT * Truck Percent	0.024	
	Total ADT * T Intersection	0.004	
	Total ADT * Left-turn Lanes	0.017	
	ITE Difference * Truck Percent	0.010	
	ITE Difference * Left-turn Lanes	0.030	
	Frontage * Left-turn Lanes	0.031	
All Crashes	Camera	0.000	0.679
	Total ADT	0.045	
	Frontage	0.000	
	Left-turn Lanes	0.000	
	Speed Limit	0.041	
	Camera * Curb Cuts	0.000	
	Camera * Grade	0.006	
	Total ADT * ITE Difference	0.006	
	Total ADT * Truck Percent	0.001	
	Total ADT * Frontage	0.010	
	Total ADT * T Intersection	0.000	
	Total ADT * Curb Cuts	0.002	
	Truck Percent * Frontage	0.002	
	Truck Percent * Design Speed	0.030	
	Truck Percent * Grade	0.019	
	Frontage * Curb Cuts	0.003	
	Frontage * Left-turn Lanes	0.002	
	Frontage * Grade	0.000	
	Curb Cuts * Design Speed	0.009	

Table F7. Results of ANOVA with a Site Identifier for Falls Church

Crash Type	Main or Second-order Effects	*p*-Value	Adjusted R^2
Rear-end Crashes	Site	0.033	0.160
Red Light Running Crashes	Site Identifier	0.000	0.617
	Truck Percent	0.056	
Angle Crashes	Site Identifier	0.000	0.580
Injury Red Light Running Crashes	Site Identifier	0.009	0.257
Injury Crashes	Site Identifier	0.000	0.491
All Crashes	Site Identifier	0.000	0.677

Table F8. Results of ANOVA with Geometric Data for Falls Church

Crash Type	Main or Second-order Effects	*p*-Value	Adjusted R^2
Rear-end Crashes	T Intersection	0.074	-0.049
Red Light Running Crashes	T Intersection	0.001	0.364
Angle Crashes	T Intersection	0.008	0.128
Injury Red Light Running Crashes	T Intersection	0.004	0.266
	Camera * Left-turn Lanes	0.090	
	Truck Percent * Curb Cuts	0.042	
Injury Crashes	T Intersection	0.037	0.134
All Crashes	T Intersection	0.009	0.138
	Camera * Left-turn Lanes	0.079	

Table F9. Results of ANOVA with a Site Identifier for Vienna

Crash Type	Main or Second-order Effects	*p*-Value	Adjusted R^2
Rear-end Crashes	No significant variables	---	0.430
Red Light Running Crashes	No significant variables	---	-0.114
Angle Crashes	No significant variables	---	0.421
Injury Red Light Running Crashes	No significant variables	----	0.031
Injury Crashes	Truck Percent	0.048	0.467
All Crashes	No significant variables	---	0.245

Table F10. Results of ANOVA with Site Identifier for All Jurisdictions

Crash Type	Main or Second-order Effects	*p*-Value	Adjusted R^2
Rear-end Crashes	Site Identifier	0.000	0.689
	Total ADT * Truck Percent	0.044	
	Site Identifier	0.000	0.871
	Camera * Total ADT	0.015	
Angle Crashes	Site Identifier	0.000	0.683
Injury Red Light Running Crashes	Site Identifier	0.000	0.759
	Truck Percent	0.097	
	Camera * Total ADT	0.083	
	Total ADT * Truck Percent	0.090	
	Site Identifier	0.000	0.775
All Crashes	Site Identifier	0.000	0.841
	Total ADT	0.051	
	Camera * Total ADT	0.005	
	Camera * ITE Difference	0.095	

Table F11. Results of ANOVA with Geometric Data for All Jurisdictions

Crash Type	Main or Second-order Effects	*p*-Value	Adjusted R^2
Rear-end Crashes	Frontage	0.003	0.574
	Curb Cuts	0.001	
	Left-turn Lanes	0.000	
	Camera * Left-turn Lanes	0.042	
	Total ADT * Truck Percent	0.000	
	Total ADT * Frontage	0.029	
	Total ADT * Curb Cuts	0.000	
	ITE Difference * Curb Cuts	0.000	
	ITE Difference * Left-turn Lanes	0.002	
	Truck Percent * Curb Cuts	0.002	
	Frontage * Curb Cuts	0.002	
	Curb Cuts * Left-turn Lanes	0.000	
	Curb Cuts * Speed Limit	0.008	
	Left-turn Lanes * Speed Limit	0.003	
Red Light Running Crashes	Frontage	0.003	0.416
	T Intersection	0.029	
	Through Lanes	0.014	
	Left-turn Lanes	0.023	
	Total ADT * Frontage	0.028	
	Total ADT * Curb Cuts	0.000	
	Total ADT * Through Lanes	0.000	
	Total ADT * SpeedLimit	0.000	
	Total ADT * Speed Limit	0.001	
	Frontage * Design Speed	0.045	
	T Intersection * Curb Cuts	0.010	
	T Intersection * Left-turn Lanes	0.003	
	Curb Cuts * Through Lanes	0.000	
	Curb Cuts * Speed Limit	0.021	
	Curb Cuts * Design Speed	0.016	
	Through Lanes * Design Speed	0.022	
	Through Lanes * Grade	0.005	

Crash Type	Main or Second-order Effects	*p*-Value	Adjusted R^2
Angle Crashes	Through Lanes	0.001	0.425
	Left-turn Lanes	0.006	
	Design Speed	0.002	
	Camera * Total ADT	0.008	
	Total ADT * Truck Percent	0.033	
	Total ADT * Left-turn Lanes	0.000	
	Truck Percent * Frontage	0.026	
	Truck Percent * Curb Cuts	0.006	
	Truck Percent * Left-turn Lanes	0.000	
	Frontage * Curb Cuts	0.005	
	Frontage * Grade	0.013	
	Curb Cuts * Speed Limit	0.008	
	Frontage * Grade	0.004	
	Through Lanes * Left-turn Lanes	0.025	
	Through Lanes * Grade	0.000	
Injury Red Light Running Crashes	Total ADT	0.030	0.290
	Frontage	0.024	
	Left-turn Lanes	0.000	
	Speed Limit	0.001	
	Camera * Curb Cuts	0.010	
	Total ADT * Curb Cuts	0.000	
	Total ADT * Left-turn Lanes	0.000	
	Curb Cuts * Through Lanes	0.007	
	Through Lanes * Left-turn Lanes	0.017	
Injury Crashes	Total ADT	0.011	0.468
	Through Lanes	0.000	
	Camera * Left-turn Lanes	0.021	
	Camera * Speed Limit	0.029	
	Total ADT * Curb Cuts	0.006	
	Total ADT * Through Lanes	0.000	
	Total ADT * Left-turn Lanes	0.000	
	ITE Difference * Left-turn Lanes	0.000	
	Frontage * Curb Cuts	0.041	
	Curb Cuts * Through Lanes	0.011	
	Curb Cuts * Left-turn Lanes	0.002	
	Curb Cuts * Speed Limit	0.022	
	Through Lanes * Left-turn Lanes	0.010	
	Through Lanes * Grade	0.001	
	Left-turn Lanes * Grade	0.008	
All Crashes	Through Lanes	0.001	0.547
	Left-turn Lanes	0.043	
	Camera * Total ADT	0.027	
	Total ADT * Curb Cuts	0.020	
	Total ADT * Through Lanes	0.000	
	Total ADT * Left-turn Lanes	0.000	
	ITE Difference * Left-turn Lanes	0.007	
	Curb Cuts * Through Lanes	0.032	
	Curb Cuts * Left-turn Lanes	0.000	

Crash Type	Main or Second-order Effects	*p*-Value	Adjusted R^2
	Curb Cuts * Speed Limit	0.001	
	Through Lanes * Left-turn Lanes	0.015	
	Through Lanes * Grade	0.001	
	Left-turn Lanes * Grade	0.011	

APPENDIX G

GLM RESULTS

Main Effects and Two-Way Interaction Effects

Tables G1 through G6 provide the *p*-values for the variables that comprise the generalized linear models for each crash type. In these tables, the variable "Camera" was always kept as one of the independent variables, regardless of its *p*-value. A plus sign (+) indicates the variable increased crashes, and a minus sign (–) indicates the variable decreased crashes. The values in parentheses are the corresponding *p*-values. For example, the first row of Table G1 shows that the presence of a camera was correlated with an increase in rear-end crashes in Arlington and the *p*-value for the variable is 0.05.

The variables in Tables G1 through G6 are defined as follows:

- Camera = indicator variable for presence of camera
- logAADT = logarithm of annual average daily traffic of minor and major road combined
- ITE Difference = yellow interval on major road + grace period – ITE recommended yellow interval
- Through Lanes = number of through lanes on both roads
- Left-turn Lanes = number of left-turn lanes on both roads
- Truck Percent = percentage of trucks in traffic stream
- T Intersection = indicator variable if intersection is or is not a three-way intersection
- Curb Cuts = indicator variable for presence of curb cuts
- Design Speed = design speed of intersection
- SpeedLimit = speed limit for intersection
- Grade = intersection grade for major road
- Frontage = indicator variable for presence of frontage road.

Tables G7 and G8 report the Fairfax City results based on four possibilities for the main effects of the camera: using either Adjustment Technique A or B and using either major ADT or total ADT. As will be shown in Table H8 in Appendix H, the GLM method with major ADT (Adjustment Technique B) yielded the fewest conflicts with the EB method for the camera's main effect.

Table G1. *p*-Values for Main and Two-Way Interaction Effects Pertaining to Rear-end Crashes

Parameter	Arlington	Fairfax City		Fairfax City		Fairfax County	Falls Church	Vienna
	Total ADT	Total ADT		Major ADT		Total ADT	Total ADT	Total ADT
		App. A	App. B	App. A	App. B			
Camera	+(0.00)	+(0.11)	+(0.00)	-(0.02)	+(0.00)	+(0.05)	-(0.29)	+(0.00)
Left-turn Lanes					+(0.00)	+(0.03)	-(0.08)	
CurbCuts	-(0.00)	+(0.07)	+(0.00)					
SpeedLimit						-(0.00)		
Truck Percent								+(0.00)
T-intersection				-(0.00)			-(0.00)	
logADT			+(0.00)	-(0.00)				
Camera*Left-turn Lanes								-(0.00)
Camera*CurbCuts			-(0.00)		-(0.00)			
logADT*Left-turn Lanes	+(0.00)					-(0.04)		
logADT*ITEDiff	-(0.02)	-(0.00)		+(0.00)	+(0.00)			
logADT*Truck Percent		-(0.00)		-(0.00)			-(0.27)	
logADT*SpeedLimit						+(0.00)		
logADT*Curb Cuts				+(0.00)				
Truck Percent*ITEDiff						+(0.01)	+(0.27)	
Truck Percent*Curb Cuts			-(0.00)				-(0.31)	
ITEDiff*Curb Cuts				-(0.00)				
Frontage*Left-turn Lanes				-(0.00)	-(0.01)			

A plus sign (+) indicates the variable increased crashes, and a minus sign (–) indicates the variable decreased crashes. The values in parentheses are the corresponding *p*-values.

Table G2. *p*-Values for Main and Two-Way Interaction Effects Pertaining to Red Light Running Crashes

Parameter	Arlington	Fairfax City		Fairfax City		Fairfax County	Falls Church	Vienna
	Total ADT	Total ADT		Major ADT		Total ADT	Total ADT	Total ADT
		App. A	App. B	App. A	App. B			
Camera	+(0.01)	-(0.00)	+(0.00)	-(0.05)	-(0.00)	-(0.09)	-(0.21)	-(0.47)
Through Lanes	-(0.00)				+(0.09)	-(0.12)		
Left-turn Lanes	-(0.00)	+(0.00)	-(0.06)		+(0.01)		-(0.00)	
Truck Percent						+(0.00)		+(0.22)
Curb Cuts					+(0.00)			
Design Speed		+(0.00)						
T-intersection							-(0.01)	
logADT								-(0.47)
Frontage					+(0.03)			
Camera*CurbCuts			-(0.00)					
logADT*Through Lanes		+(0.00)				+(0.01)		
logADT*Left-turn Lanes								
logADT*CurbCuts	-(0.02)	+(0.00)		+(0.00)				
logADT*SpeedLimit	+(0.00)							
logADT*Tintersection						-(0.01)		
logADT*Frontage								
Through Lanes*Grade						-(0.00)		
Left-Turn Lanes*Grade						+(0.00)		
Truck Percent *Left-turn						-(0.00)		
Frontage*Grade						+(0.00)		
Curb Cuts*SpeedLimit				-(0.00)	-(0.00)			
Frontage*DesignSpeed					-(0.04)			

A plus sign (+) indicates the variable increased crashes, and a minus sign (–) indicates the variable decreased crashes. The values in parentheses are the corresponding *p*-values.

Table G3. *p*-Values for Main and Two-Way Interaction Effects Pertaining to Angle Crashes

Parameter	Arlington	Fairfax City		Fairfax City		Fairfax County	Falls Church	Vienna
	Total ADT	Total ADT		Major ADT		Total ADT	Total ADT	Total ADT
		App. A	App. B	App. A	App. B			
Camera	+(0.00	+(0.00)	-(0.00)	+(0.00)	+(0.35)	+(0.17)	-(0.04)	+(0.00)
Through Lanes	-(0.00)				-(0.00)			
Left-turn Lanes			+(0.00)					
SpeedLimit						+(0.00)		
DesignSpeed	+(0.00)	-(0.00)						
Truck Percent		+(0.00)				+(0.00)		
T-intersection							-(0.00)	
Camera*Truck Percent		-(0.00)						
Camera*logADT			+(0.00)					
Camera*Speed Limit			-(0.00)					
logADT*Left-turn Lanes	-(0.00)		-(0.00)	+(0.00)			-(0.01)	+(0.00)
logADT*Through Lanes			+(0.00)					
logADT*CurbCuts		+(0.00)				+(0.00)	+(0.03)	-(0.00)
logADT*Truck Percent			+(0.00)					+(0.05)
Through Lanes*Grade		-(0.00)			+(0.00)			
Through Lanes*Truck				+(0.03)				
Through Lanes*Left-turn				-(0.00)				
SpeedLimit*Truck Perc		-(0.00)	-(0.00)	-(0.07)				
SpeedLimit*CurbCuts					-(0.00)	-(0.00)		
DesignSpeed*Truck Percent						-(0.00)		
Frontage*Grade						+(0.01)		
Frontage*CurbCuts								

A plus sign (+) indicates the variable increased crashes, and a minus sign (–) indicates the variable decreased crashes. The values in parentheses are the corresponding *p*-values.

Table G4. *p*-Values for Main and Two-Way Interaction Effects Pertaining to Red Light Running Injury Crashes

Parameter	Arlington	Fairfax City		Fairfax City		Fairfax County	Falls Church	Vienna
	Total ADT	Total ADT		Major ADT		Total ADT	Total ADT	Total ADT
		App. A	App. B	App. A	App. B			
Camera	+(0.03)	-(0.08)	-(0.00)	-(0.05)	-(0.00)	-(0.08)	-(0.38)	-(0.67)
Left-turn Lanes				-(0.07)		+(0.00)	-(0.12)	
SpeedLimit		-(0.00)				+(0.00)		
Design Speed						+(0.01)		
logADT							-(0.36)	+(0.15)
T-intersection							-(0.06)	
Camera*Truck			+(0.00)		+(0.01)			
logADT*Through Lanes				-(0.08)		+(0.09)		
logADT*Left-turn Lanes			+(0.04)					
logADT*Truck Percent	+(0.16)	-(0.08)						
logADT*SpeedLimit			-(0.00)	-(0.00)	-(0.00)			
ThruLanes*Left-turn Lanes	-(0.00)			+(0.03)	+(0.00)			
Left-turn Lanes*SpeedLimit						-(0.00)		
Truck Percent*CurbCuts	-(0.00)		-(0.00)					
Frontage*Grade						+(0.01)		

A plus sign (+) indicates the variable increased crashes, and a minus sign (–) indicates the variable decreased crashes. The values in parentheses are the corresponding *p*-values.

Table G5. *p*-Values for Main and Two-Way Interaction Effects Pertaining to Injury Crashes

Parameter	Arlington	Fairfax City		Fairfax City		Fairfax County	Falls Church	Vienna
	Total ADT	Total ADT		Major ADT		Total ADT	Total ADT	Total ADT
		App. A	App. B	App. A	App. B			
Camera	+(0.00)	+(0.10)	-(0.00)	-(0.04)	-(0.05)	+(0.04)	+(0.08)	+(0.04)
Through Lanes	-(0.00)	-(0.14)	+(0.00)	+(0.00)	+(0.00)			
Truck Percent								+(0.00)
DesignSpeed				-(0.00)	-(0.00)			
logADT								+(0.36)
Camera*Truck					+(0.09)			
Camera*Speed Limit			-(0.00)					
Camera*logADT			+(0.00)					
logADT*Through Lanes				-(0.00)		+(0.00)		
logADT*Left-turn Lanes			-(0.00)	-(0.00)	-(0.00)	+(0.00)		
logADT*CurbCuts				+(0.00)	+(0.00)	+(0.00)		
logADT*Speed Limit					-(0.00)			
Through Lanes*Grade	-(0.00)		-(0.00)	-(0.00)	-(0.00)			
Through Lanes*Left-turn Lane	+(0.00)			+(0.00)				
Left-turn Lanes*CurbCuts			+(0.00)		+(0.00)	-(0.00)		
Through Lanes*CurbCuts							+(0.00)	
CurbCuts*T-intersection							-(0.01)	
ITEDiff*Left-Turn Lanes	-(0.00)	+(0.00)		+(0.00)			-(0.08)	

A plus sign (+) indicates the variable increased crashes, and a minus sign (–) indicates the variable decreased crashes. The values in parentheses are the corresponding *p*-values.

Table G6. *p*-Values for Main and Two-Way Interaction Effects Pertaining to Total Crashes

Parameter	Arlington	Fairfax City		Fairfax City		Fairfax County	Falls Church	Vienna
	Total ADT	Total ADT		Major ADT		Total ADT	Total ADT	Total ADT
		App. A	App. B	App. A	App. B			
Camera	+(0.00)	+(0.01)	+(0.01)	+(0.02)	+(0.00)	+(0.02)	-(0.02)	+(0.08)
Frontage						+(0.00)		
Through Lanes	-(0.00)							
Truck Percent		-(0.00)	-(0.00)					+(0.00)
T-intersection							-(0.00)	
logADT					+(0.02)			
Camera*Grade		-(0.01)	-(0.00)		-(0.00)			
logADT*Curb Cuts		+(0.04)					+(0.06)	
logADT*Left-turn Lanes	+(0.00)		-(0.00)		-(0.00)	+(0.01)	-(0.02)	
logADT*Through Lanes				-(0.00)				
logADT*Truck Percent						+(0.01)		
Through Lanes*Grade				+(0.01)	-(0.00)			
Through Lanes*Left-turn				+(0.01)				
CurbCuts*Left-turn Lanes	-(0.00)		+(0.00)		+(0.00)			
CurbCuts*SpeedLimit	+(0.00)		-(0.00)	-(0.00)	-(0.00)			

A plus sign (+) indicates the variable increased crashes, and a minus sign (–) indicates the variable decreased crashes. The values in parentheses are the corresponding *p*-values.

Table G7. GLM Results (Camera Main Effects) for Fairfax City: Comparison of Adjustment Technique A and Adjustment Technique B[a]

Crash Type	Adjustment Technique A	Adjustment Technique B
Rear-end	-(0.02)	+(0.00) [b]
Red Light Running	-(0.05)	-(0.00)
Angle	+(0.00)	+(0.35)
Red Light Running Injury	-(0.05)	-(0.00) [c]
Total Injury	-(0.04)	-(0.05) [d]
Total	+(0.02)	+(0.00)[e]

[a]Results based on GLM analysis using major ADT.
[b]There was an interaction effect of camera and curb cuts, significant decrease with $p = 0.00$. The combination of the main effect and interaction effect meant that the magnitude of increase in rear-end crashes decreased when curb cuts are present (10% of the cases). However, the combination of main and interaction effect was consistently an increase for rear-end crashes.
[c]There was an interaction effect of camera and truck percentage (significant increase with $p = 0.01$). The combination of the main effect and interaction effect meant that crashes decreased in 60% of the cases and increased in 40% of the crashes.
[d]There was an interaction effect of camera and truck (nonsignificant increase with $p = 0.09$; the nonsignificant interaction is retained because without it the main effect of camera becomes nonsignificant). The combination of the main effect and interaction effect meant that crashes decreased in 60% of the cases and increased in 40% of the cases.
[e]There was an interaction effect of camera and grade (significant decrease with $p = 0.00$). The combination of the main effect and interaction effect meant that the magnitude of increase in total crashes decreased with an increase in grade. However, there were no observed cases where the grade was steep enough for the effect to become a decrease.

Table G8. GLM Results for Fairfax City: Comparison of Adjustment Technique A and Adjustment Technique B[a]

Crash Type	Adjustment Technique A	Adjustment Technique B
Rear-end	+(0.11)	+(0.00) [b]
Red Light Running	-(0.00)	+(0.00) [c]
Angle	+(0.00) [d]	-(0.00) [e]
Red Light Running Injury	-(0.08)	-(0.00) [f]
Total Injury	+(0.10)	-(0.00) [g]
Total	+(0.01) [h]	+(0.01) [i]

[a]Results based on GLM analysis using total ADT.
[b]There was an interaction effect of camera and curb cuts (significant decrease with $p = 0.00$). The combination of the main effect and interaction effect meant that the magnitude of increase in rear-end crashes decreased when curb cuts are present (10% of the cases). As was the case in Table G7, the combination of main and interaction effect was consistently an increase for rear-end crashes.
[c]There was an interaction effect of camera and curb cuts (significant decrease with $p = 0.00$). The combination of the main effect and interaction effect meant that crashes increased in 10% of the cases and decreased in 90% of the cases. This is the only known conflict in Tables G7 and G8 between the main effect and the sum of main plus interaction effects: the main effect of camera showed an increase but the main effect of camera added to the interaction effects showed a decrease (in 90% of the cases).
[d]There was an interaction effect of camera and truck percentage (significant decrease with $p = 0.00$). The combination of the main effect and interaction effect meant that crashes increased in 67% of the cases and decreased in 33% of the cases.
[e]There were two interaction effects, one between camera and total ADT (significant increase with p = 0.00) and another between camera and speed limit (significant decrease with p = 0.00). The combination of the main effect and interaction effects meant that the magnitude of decrease in crashes decreased with increase in total ADT and increased with increase in speed limits.
[f]There was an interaction effect of camera and truck percentage (significant increase with p = 0.00). The combination of the main effect and interaction effect meant that crashes decreased in 60% of the cases and increased in 40% of the crashes.
[g]There were two interaction effects, one between camera and total ADT (significant increase with $p = 0.00$) and another between camera and speed limit (significant decrease with $p = 0.00$). The combination of the main effect and interaction effects meant that the magnitude of decrease in crashes decreased with increase in total ADT and increased with increase in speed limits.
[h]There was an interaction effect of camera and grade, significant decrease with $p = 0.01$. The combination of the main effect and interaction effect meant that the magnitude of increase in total crashes decreased with increase in grade. However, there were no observed cases where the grade was steep enough for the effect to become a decrease.
[i]There was an interaction effect of camera and grade, significant decrease with $p = 0.00$. The combination of the main effect and interaction effect meant that the magnitude of increase in total crashes decreased with increase in grade. However, there were no observed cases where the grade was steep enough for the effect to become a decrease.

GLM Equations

The crash estimation equations developed for each crash type for each jurisdiction are as follows:

Arlington

$$\text{Rear End Crashes} = \exp(2.31 + 0.55 * \text{Camera} - 0.86 * \text{Curb Cuts} \\ -0.10 * \text{logAADT} * \text{ITEDiff} + 0.04 * \text{logAADT} * \text{Number of Left Turn Lanes})$$

$$\text{Red Light Running Crashes} = \exp(2.93 + 0.57 * \text{Camera} - 1.13 * \text{Number of Through Lanes} \\ -0.81 * \text{Number of Left Turn Lanes} - 0.07 * \text{logAADT} * \text{Curb Cuts} \\ +0.01 * \text{logAADT} * \text{Speed Limit})$$

$$\text{Angle Crashes} = \exp(2.54 + 0.36 * \text{Camera} - 0.87 * \text{Number of Through Lanes} \\ +0.09 * \text{Design Speed} - 0.04 * \text{logAADT} * \text{Number of Left Turn Lanes})$$

$$\text{Red Light Running Injury Crashes} = \exp(1.12 + 0.71 * \text{Camera} + 0.09 * \text{logAADT} * \text{Truck Percentage} \\ - 0.18 * \text{Number of Through Lanes} * \text{Number of Left Turn Lanes} \\ - 1.46 * \text{Truck Percentage} * \text{Curb Cuts})$$

$$\text{Total Injury Crashes} = \exp(14.49 + 0.58 * \text{Camera} - 3.21 * \text{Number of Through Lanes} \\ - 6.44 * \text{ITEdiff} * \text{Number of Left Turn Lanes} - 0.23 * \text{Grade} * \text{Number of Through Lanes} \\ +1.81 * \text{Number of Through Names} * \text{Number of Left Turn Lanes})$$

$$\text{Total Crashes} = \exp(2.84 + 0.42 * \text{Camera} - 0.59 * \text{Number of Through Lanes} \\ - 0.15 * \text{logAADT} * \text{Number of Left Turn Lanes} + 0.07 * \text{Curb Cuts} * \text{Speed Limit})$$

Fairfax City (using Total ADT and Adjustment Technique A)

$$\text{Rear End Crashes} = \exp(2.81 + 0.22 * \text{Camera} + 0.61 * \text{Curb Cuts} - 0.01 * \text{logAADT} * \text{Truck Percentage} - 0.99 * \text{Curb Cuts} * \text{ITEDiff})$$

$$\text{Red Light Running Crashes} = \exp(-15.61 - 0.95 * \text{Camera} + 0.54 * \text{Number of Left Turn Lanes} + 0.06 * \text{Design Speed} + 0.22 * \text{logAADT} * \text{Number of Through Lanes} + 0.20 * \text{logAADT} * \text{Curb Cuts})$$

$$\text{Angle Crashes} = \exp(3.96 + 1.48 * \text{Camera} - 0.05 * \text{Design Speed} + 2.72 * \text{Truck Percentage} + 0.47 * \text{logAADT} * \text{Curb Cuts} - 0.46 * \text{Truck Percentage} * \text{Camera} - 0.63 * \text{Number of Through Lanes} * \text{Grade} - 0.08 * \text{Truck Percentage} * \text{Speed Limit})$$

$$\text{Red Light Running Injury Crashes} = \exp(6.66 - 0.74 * \text{Camera} - 0.19 * \text{Speed Limit} - 0.02 * \text{logAADT} * \text{Truck Percentage})$$

$$\text{Total Injury Crashes} = \exp(1.86 + 0.23 * \text{Camera} - 0.12 * \text{Number of Through Lanes} + 0.19 * \text{Number of Left Turn Lanes} * \text{ITEDiff})$$

$$\text{Total Crashes} = \exp(2.23 + 1.37 * \text{Camera} - 0.12 * \text{Truck Percentage} + 0.10 * \text{logAADT} * \text{Curb Cuts} - 0.65 * \text{Camera} * \text{Grade})$$

Fairfax City (using Major ADT and Adjustment Technique A)

$$\text{Rear End Crashes} = \exp(25.99 - 0.30 * \text{Camera} - 4.95 * \text{logAADT} - 1.64 * \text{T - intersection} + 4.62 * \text{logAADT} * \text{ITEDiff} - 0.01 * \text{logAADT} * \text{Truck Percentage} + 2.52 * \text{logAADT} * \text{Curb Cuts} - 45.76 * \text{ITEDiff} * \text{Curb Cuts} - 0.45 * \text{Frontage} * \text{Number of Left Turn Lanes})$$

$$\text{Red Light Running Crashes} = \exp(0.81 - 0.49 * \text{Camera} + 0.68 * \text{logAADT} * \text{Curb Cuts} - 0.22 * \text{Curb Cuts} * \text{Speed Limit})$$

$$\text{Angle Crashes} = \exp(1.32 + 0.65 * \text{Camera} + 0.07 * \text{logAADT} * \text{Number of Left Turn Lanes} * \text{Grade} - 0.15 * \text{Number of Left Turn Lanes} * \text{Number ofThrough Lanes} - 0.01 * \text{Truck Percentage} * \text{Speed Limit} + 0.06 * \text{Number of Thruough Lanes} * \text{Truck Percentage})$$

$$\text{Red Light Running Injury Crashes} = \exp(11.50 - 0.84 * \text{Camera} - 1.46 * \text{Number of Left Turn Lanes} + 0.40 * \text{Number of Left Turn Lanes} * \text{Number of Through Lanes} - 0.03 * \text{logAADT} * \text{Speed Limit} - 0.06 * \text{logAADT} * \text{Number of Through Lanes})$$

Total Injury Crashes = exp (-53.55 - 0.32 * Camera - 23.49 * Number of Through Lanes
-0.11 * Design Speed – 0.50 * logAADT * Number of Left Turn Lanes
-1.06 * logAADT * Number of Through Lanes + 3.93 * Number of Left Turn Lanes * ITEDiff
-6.61 * Number of Through Lanes * Grade + 6.07 * logAADT * Curb Cuts
+0.55 * Number of Left Turn Lanes * Number of Through Lanes)

Total Crashes = exp (6.03 + 0.30 * Camera - 0.07 * logAADT * Number of Through Lanes
+0.17 * Number of Through Lanes * Grade - 0.06 * Curb Cuts * Speed Limit
+0.03 * Number of Through Lanes * Number of Left Turn Lanes)

Fairfax City (using Total ADT and Adjustment Technique B)

Rear End Crashes = exp (-8.80 + 1.86 * Camera + 0.86 * logADT + 1.95 * Curb Cuts
-1.85 * Camera * Curb Cuts - 0.10 * Truck Percentage * Curb Cuts)

Red Light Running Crashes = exp (-23.87 + 25.23 * Camera - 0.17 * Number of Left Turn Lanes
+24.96 * Curb Cuts - 25.25 * Camera * Curb Cuts)

Angle Crashes = exp (-7.43 - 28.22 * Camera + 18.20 * Number of Left Turn Lanes
-1.54 * logADT * Number of Left Turn Lanes + 3.24 * Camera * logADT
+0.15 * logADT * Truck Percentage - 0.05 * Speed Limit * Truck Percentage
+0.14 * logADT * Number of Through Lanes - 0.24 * Camera * Speed Limit)

Red Light Running Injury Crashes = exp (9.22 - 2.30 * Camera - 0.39 * Truck Percentage * Curb Cuts
–0.03 * logADT * Speed Limit + 0.05 * logADT * Number of Left Turn Lanes
+0.57 * Camera * Truck Percentage)

Total Injury Crashes = exp (-5.32 - 35.95 * Camera + 9.83 * Number of Through Lanes
−1.23 * logADT * Number of Left Turn Lanes - 4.32 * Number of Through Lanes * Grade
+14.40 * Number of Left Turn Lanes * Curb Cuts - 0.30 * Camera * Speed Limit
+4.11 * Camera * logADT)

Total Crashes = exp (6.80 + 1.34 * Camera - 0.09 * Truck – 0.79 * Camera * Grade
+1.85 * Curb Cuts * Number of Left Turn Lanes - 0.14 * Curb Cuts * Speed Limit
-0.13 * logADT * Number of Left Turn Lanes)

Fairfax City (using Major ADT and Adjustment Technique B)

Rear End Crashes = exp (-0.05 + 0.95 * Camera + 0.35 * Number of Left Turn Lanes
-0.93 * Camera * Curb Cuts + 0.14 * logADT * ITEDiff
-0.30 * Number of Left Turn Lanes * Frontage)

Red Light Running Crashes = exp (-3.28 - 0.79 * Camera + 6.00 * Frontage + 9.77 * Curb Cuts
+0.54 * Number of Through Lanes + 0.65 * Number of Left Turn Lanes
-0.10 * Frontage * Design Speed - 0.30 * Curb Cuts * Speed Limit)

Angle Crashes = exp (7.21 + 0.19 * Camera - 1.04 * Number of Through Lanes
+0.38 * Number of Through Lanes * Grade - 0.12 * Curb Cuts * Speed Limit)

Red Light Running Injury Crashes = exp (6.56 - 1.37 * Camera + 0.31 * Camera * Truck
+0.13 * Number of Through Lanes * Number of Left Turn Lanes - 0.02 * logADT * Speed Limit)

Total Injury Crashes = exp (-45.22 - 0.39 * Camera + 21.15 * Number of Through Lanes
-0.03 * Design Speed - 1.43 * logADT * Number of Left Turn Lanes
-10.56 * Number of Through Lanes * Grade0.03 * logADT * Speed Limit
+15.41 * Number of Left Turn Lanes * Curb Cuts + 5.53 * logADT * Curb Cuts
- + 0.08 * Camera * Truck)

Total Crashes = exp (-4.95 + 1.81 * Camera + 1.34 * logADT - 0.89 * Camera * Grade
-0.24 * logADT * Number of Left Turn Lanes + 2.66 * Curb Cuts * Number of Left Turn Lanes
–0.12 * Grade * Number of Through Lanes - 0.16 * Curb Cuts * Speed Limit)

Fairfax County

Rear End Crashes = exp(2.04 + 0.27 * Camera + 5.50 * Number of Left Turn Lanes
-0.78 * Speed Limit - 0.49 * logAADT * Number of Left Turn Lanes
+0.07 * logAADT * Speed Limit + 0.06 * ITEDiff * Truck Percentage)

Red Light Running Crashes = exp(-2.51 - 0.40 * Camera - 0.77 * Number of Through Lanes
+0.36 * Truck Percentage + 0.12 * logAADT * Number of Through Lanes
- 0.14 * logAADT * T - intersection - 0.25 * Number of Through Lanes * Grade
+ 0.54 * Grade * Number of Left Turn Lanes
- 0.14 * Truck Percentage * Number of Left Turn Lanes + 0.33 * Frontage * Grade)

Angle Crashes = exp(-2.69 + 0.22 * Camera + 0.09 * Speed Limit + 0.50 * Truck Percentage
+ 0.70 * logAADT * Curb Cuts - 0.18 * Speed Limit * Curb Cuts + 0.17 * Frontage * Grade
- 0.01 * Truck Percentage * Design Speed)

Red Light Running Injury Crashes = exp(-16.59 - 0.52 * Camera + 4.84 * Number of Left Turn Lanes
+ 0.27 * Speed Limit + 0.03 * Design Speed + 0.02 * logAADT * Number of Through Lanes
+ 0.30 * Frontage * Grade - 0.10 * Number of Left Turn Lanes * Speed Limit)

Total Injury Crashes = exp(-0.77 - 0.32 * Camera + 0.02 * logAADT * Number of Through Lanes
+ 0.04 * logAADT * Number of Left Turn Lanes + 0.14 * logAADT * Curb Cuts
-0.70 * Curb Cuts * Number of Left Turn Lanes)

Total Crashes = exp(2.00 + 0.34 * Camera + 0.40 * Frontage
+ 0.01 * logAADT * Number of Left Turn Lanes + 0.01 * logAADT * Truck Percentage)

Falls Church

$$\text{Rear End Crashes} = \exp(0.75 - 0.53 * \text{Camera} - 0.37 * \text{Number of Left Turn Lanes} - 1.14 * \text{T-intersection} - 0.24 * \text{logAADT} * \text{Truck Percentage} + 2.66 * \text{Truck Percentage} * \text{ITE Difference} - 1.24 * \text{Truck Percentage} * \text{CurbCuts})$$

$$\text{Red Light Running Crashes} = \exp(0.71 - 0.63 * \text{Camera} - 0.72 * \text{Number of Left Turn Lanes} - 2.65 * \text{T-intersection})$$

$$\text{Angle Crashes} = \exp(0.72 - 1.27 * \text{Camera} - 0.95 * \text{T-intersection} - 0.04 * \text{logAADT} * \text{Number of Left Turn Lanes} + 0.08 * \text{logAADT} * \text{Curb Cuts})$$

$$\text{Red Light Running Injury Crashes} = \exp(10.07 - 0.53 * \text{Camera} - 0.98 * \text{logAADT} - 0.44 * \text{logAADT} * \text{Number of Left Turn Lanes} - 1.60 * \text{T-intersection})$$

$$\text{Total Injury Crashes} = \exp(-0.12 + 0.51 * \text{Camera} - 0.88 * \text{Curb Cuts} * \text{T-intersection} + 0.34 * \text{Number of Through Lanes} * \text{Curb Cuts} - 0.14 * \text{Number of Left Turn Lanes} * \text{ITE Difference})$$

$$\text{Total Crashes} = \exp(1.75 - 0.86 * \text{Camera} - 0.02 * \text{logAADT} * \text{Number of Left Turn Lanes} + 0.05 * \text{logAADT} * \text{Curb Cuts} - 0.85 * \text{T-intersection})$$

Vienna

$$\text{Rear End Crashes} = \exp(0.65 + 2.31 * \text{Camera} - 1.27 * \text{Camera} * \text{Number of Left Turn Lanes} + 0.21 * \text{Truck Percentage})$$

$$\text{Red Light Running Crashes} = \exp(14.20 - 0.85 * \text{Camera} + 0.25 * \text{Truck Percentage} - 1.53 * \text{logAADT})$$

$$\text{Angle Crashes} = \exp(20.24 + 1.10 * \text{Camera} + 0.24 * \text{logAADT} * \text{Number of Left Turn Lanes} + 0.01 * \text{logAADT} * \text{Truck Percentage} - 2.28 * \text{logAADT} * \text{Curb Cuts})$$

$$\text{Red Light Running Injury Crashes} = \exp(-48.55 - 0.71 * \text{Camera} + 4.26 * \text{logAADT})$$

$$\text{Total Injury Crashes} = \exp(-4.87 + 0.46 * \text{Camera} + 0.21 * \text{Truck Percentage} + 0.46 * \text{logAADT})$$

$$\text{Total Crashes} = \exp(1.75 + 0.28 * \text{Camera} + 0.12 * \text{Truck Percentage})$$

APPENDIX H

EMPIRICAL BAYES RESULTS

Tables H1 through H6 summarize the results of the EB analysis. The third, fourth, and fifth columns indicate the lower bound, estimate, and upper bound of Θ, which is the impact on crashes. For example, the first row of Table H1 suggests that the estimate of θ is 2.39, meaning that the cameras are correlated with a 139% increase in rear-end crashes in Arlington County. The lower bound of this increase is 194%, and the upper bound of this increase is 284%. Because 1.00 is not included between the lower and upper bound, the Empirical Bayes results shows that the increase in rear-end crashes for Arlington County is statistically significant. The three rightmost columns show, respectively, the maximum likelihood estimate that results from the calibration procedure, the dispersion parameter (*k*), and the total number of sites (camera sites plus untreated sites) studied with the EB procedure.

As noted in the text, the Fairfax City cameras were installed in May 1998, which yielded only 4 months of before data (January-April of that year. Thus, these 4 months of before data were converted to a year of before data and were used as the basis for crash estimation models for Fairfax City. Adjustment Technique A was followed both for the individual Fairfax City results and for the aggregate results with all jurisdictions combined. Thus, for Fairfax City, the after period consisted of January 1999 through December 2004, which excluded the eight after months of May 1998 – December 1998. (However, as shown in Table H7 and as described in the text, Adjustment Technique B yields similar results as Adjustment Technique A for the EB analysis.)

Finally, Table H8 compares the directional results of the EB method (using major ADT) and GLM (using major ADT, total ADT, Adjustment Technique A, and Adjustment Technique B). It is apparent that use of GLM major ADT with Adjustment Technique B yields the fewest number of conflicts with the EB method.

Table H1. Empirical Bayes Results for Rear-end Crashes

Jurisdiction	Based on	θ (Lower Bound)	θ (estimate)	θ (Upper Bound)	Maximum Likelihood	*k*	Total Sites
Arlington County	Total Volumes	1.94	2.39	2.84	52.90	96.35	6
Fairfax City	Major ADT	0.93	1.10	1.27	217.29	6.94	8
Fairfax County	Total Volumes	1.22	1.40	1.58	2250.52	1.59	40
Fairfax County	Major ADT	1.16	1.31	1.45	2330.55	1.40	46
Falls Church	Major ADT	1.04	2.36	3.69	-2.81	4.48	6
Vienna	Major ADT	1.24	1.64	2.04	92.05	115.31	6
All Jurisdictions	Major ADT	1.31	1.42	1.54	2644.98	1.75	72

Table H2. Empirical Bayes Results for Red Light Running Crashes

Jurisdiction	Based on	θ (Lower Bound)	Θ (estimate)	θ (Upper Bound)	Maximum Likelihood	*k*	Total Sites
Arlington County	Total Volumes	1.84	2.59	3.34	-14.74	5.74	6
Fairfax City	Major ADT	0.24	0.34	0.44	6.99	14.48	8
Fairfax County	Total Volumes	0.48	0.71	0.93	-150.00	1.72	40
Fairfax County	Major ADT	0.56	0.77	0.97	-173.78	1.60	46
Falls Church	Major ADT	-0.01	2.09	4.18	-19.09	0.85	6
Vienna	Major ADT	-0.33	0.34	1.02	-20.64	1.56	6
All Jurisdictions	Major ADT	0.78	0.92	1.07	-247.31	1.41	72

Table H3. Empirical Bayes Results for Angle Crashes

Jurisdiction	Based on	θ (Lower Bound)	θ (estimate)	θ (Upper Bound)	Maximum Likelihood	*k*	Total Sites
Arlington County	Total Volumes	1.25	1.53	1.82	74.08	80.31	6
Fairfax City	Major ADT	0.54	0.65	0.76	131.41	7.09	8
Fairfax County	Total Volumes	0.91	1.07	1.22	1126.28	1.82	40
Fairfax County	Major ADT	0.94	1.08	1.23	1129.79	1.53	46
Falls Church	Major ADT	0.34	0.85	1.36	27.14	5.84	6
Vienna	Major ADT	0.49	0.94	1.39	49.69	97.55	6
All Jurisdictions	Major ADT	1.09	1.20	1.31	1383.95	1.93	72

Table H4. Empirical Bayes Results for Injury Red Light Running Crashes

Jurisdiction	Based on	θ (Lower Bound)	θ (estimate)	θ (Upper Bound)	Maximum Likelihood	*k*	Total Sites
Arlington County	Total Volumes	0.99	1.65	2.32	-17.83	1.40	6
Fairfax City	Major ADT	0.00	0.01	0.02	-16.51	11.20	8
Fairfax County	Total Volumes	0.40	0.71	1.02	-203.23	2.07	40
Fairfax County	Major ADT	0.54	0.85	1.16	-226.84	1.92	46
Falls Church	Major ADT	-0.31	1.59	3.50	-26.05	0.92	6
Vienna	Major ADT	undefined[a]	0.00	undefined[a]	-11.86	2.16	6
All Jurisdictions	Major ADT	0.82	1.07	1.31	-316.77	1.51	72

[a]The lower and upper bounds are undefined for Vienna injury red light running crashes because there were 0 crashes during the after period.

Table H5. Empirical Bayes Results for Total Injury Crashes

Jurisdiction	Based on	θ (Lower Bound)	θ (estimate)	θ (Upper Bound)	Maximum Likelihood	*k*	Total Sites
Arlington County	Total Volumes	1.56	1.89	2.21	98.90	87.46	6
Fairfax City	Major ADT	0.79	0.95	1.12	106.14	8.01	8
Fairfax County	Total Volumes	0.88	1.03	1.19	1070.91	2.31	40
Fairfax County	Major ADT	0.92	1.06	1.20	1085.74	1.91	46
Falls Church	Major ADT	0.90	1.79	2.68	-0.92	6.80	6
Vienna	Major ADT	1.00	1.59	2.18	31.69	74.29	6
All Jurisdictions	Major ADT	1.08	1.18	1.29	1278.86	2.49	72

Table H6. Empirical Bayes Results for Total Crashes

Jurisdiction	Based on	θ (Lower Bound)	θ (estimate)	θ (Upper Bound)	Maximum Likelihood	*k*	Total Sites
Arlington County	Total Volumes	1.45	1.65	1.85	392.37	107.93	6
Fairfax City	Major ADT	0.83	0.93	1.04	662.05	8.38	8
Fairfax County	Total Volumes	1.12	1.23	1.35	6459.30	2.06	40
Fairfax County	Major ADT	1.09	1.19	1.29	6721.47	1.90	46
Falls Church	Major ADT	0.88	1.38	1.87	225.12	6.56	6
Vienna	Major ADT	0.98	1.25	1.51	398.11	90.93	6
All Jurisdictions	Major ADT	1.22	1.29	1.37	8351.48	2.36	72

Table H7. Empirical Bayes Results for Fairfax City: Comparison of Adjustment Technique A and Adjustment Technique B[a]

Crash Type	Adjustment Technique A	Adjustment Technique B
Rear-end	1.10	1.14
Red Light Running	0.34	0.35
Angle	0.65	0.64
Red Light Running Injury	0.01	0.02
Total Injury	0.95	0.93
Total	0.93	0.90

[a]Results based on EB analysis using major ADT.

Table H8. Comparison of Directional Results from EB and GLM Camera Main Effect for Fairfax City

	EB (Table H7)	**GLM (Tables G7 and G8)**			
	Major ADT	**Major ADT (Table G7)**		**Total ADT (Table G8)**	
Crash Type	**Adjustment Technique A or B**	**Adjustment Technique A**	**Adjustment Technique B**	**Adjustment Technique A**	**Adjustment Technique B**
Rear-end	Increase	Decrease	Increase[a]	Increase	Increase[b]
Red Light Running	Decrease	Decrease	Decrease	Decrease	Increase[c]
Angle	Decrease	Increase	Increase	Increase[d]	Decrease[e]
Red Light Running Injury	Decrease	Decrease	Decrease[f]	Decrease	Decrease[g]
Total Injury	Decrease	Decrease	Decrease[h]	Increase	Decrease[i]
Total	Decrease	Increase	Increase[j]	Increase[k]	Increase[l]
Conflicts between with the EB method		3	2	3	2

[a]GLM showed that cameras are always associated with an increase in rear-end crashes. This is based on the combination of the main effect of the camera (significant increase, $p = 0.00$) and the interaction effect between camera and curb cuts (significant decrease, $p = 0.00$). (The presence of one or more curb cuts greatly reduces the magnitude of this increase, which was about 10% of the cases.)

[b]GLM showed that cameras are always associated with an increase in rear-end crashes. This is based on the combination of the main effect of the camera (significant increase, $p = 0.00$) and the interaction effect between camera and curb cuts (significant decrease, $p = 0.00$). (The presence of one or more curb cuts greatly reduces the magnitude of this increase, which was about 10% of the cases.)

[c]GLM showed that cameras caused an increase in red light running crashes in the absence of curb cuts (which represented 10% of the cases) and the cameras cause a decrease in red light running crashes in the presence of one or more curb cuts at the intersection (which occurred in 90% of the cases). This is based on the combination of the main effect of the camera (significant increase, $p = 0.00$) and the interaction effect between camera and curb cuts (significant decrease, $p = 0.00$). As noted in Table G8, this is the only situation where the main effect of the camera and the sum of the main plus interaction effects yield different results.

[d]GLM showed that cameras caused an increase in angle crashes when the truck percentages are low (i.e., less than or equal to 3 percentage points, which represents 67% of the cases) and the cameras cause a decrease in angle crashes when there is a high percentage of truck (i.e., more than 3 percentage points, which represents 33% of the cases). This is based on the combination of the main effect of the camera (significant increase, $p = 0.00$) and the interaction effect between camera and truck percentage (significant decrease, $p = 0.00$).

[e]GLM showed that cameras cause a decrease in angle crashes. The magnitude of this decrease grows as speed limits increase from 25 to 35 mph. This is based on the combination of the main effect of the camera (significant decrease, $p = 0.00$) and the interaction effects between camera and total ADT (significant increase, $p = 0.00$) and camera and speed limit (significant decrease, $p = 0.00$).

[f]GLM showed that cameras cause a decrease in red light running injury crashes when the truck percentages are low (i.e., less than or equal to 4 percentage points, which represents 60% of the crashes) and the cameras cause an increase with high truck percentages (i.e., more than 4 percentage points, which represents 40% of the cases). This is based on the combination of the main effect of the camera (significant decrease, $p = 0.00$) and the interaction effect between camera and truck percentage (significant increase, $p = 0.01$).

[g]GLM showed that cameras cause a decrease in red light running injury crashes when the truck percentages are low (i.e., less than or equal to 4 percentage points, which represents 60% of the crashes) and the cameras cause an increase with high truck percentages (i.e., more than 4 percentage points, which represents 40% of the cases). This is based on the combination of the main effect of the camera (significant decrease, $p = 0.00$) and the interaction effect between camera and truck percentage (significant increase, $p = 0.00$).

[h]GLM showed that cameras cause a decrease in total injury crashes when the truck percentages are low (i.e., less than or equal to 4 percentage points, which represents 60% of the cases) and the cameras cause an increase with high truck percentages (i.e., more than 4 percentage points, which represents 40% of the cases). This is based on the combination of the main effect of the camera (significant decrease, $p = 0.05$) and the interaction effect between camera and truck percentage (nonsignificant increase, $p = 0.08$).

[i]GLM showed that cameras cause a decrease in total injury crashes whose magnitude goes up with higher speed limits and lower volumes. This is based on the combination of the main effect of the camera (significant decrease, *p*

= 0.00) and the interaction effects between camera and total ADT (significant increase, $p = 0.00$) and camera and speed limit (significant decrease, $p = 0.00$).
[j]GLM showed that cameras are associated with an increase in total injury crashes. This is based on the combination of the main effect of the camera (significant increase, $p = 0.01$) and the interaction effects between camera and grade (significant decrease, $p = 0.01$).
[k]GLM showed that cameras are associated with an increase in total injury crashes. This is based on the combination of the main effect of the camera (significant increase, $p = 0.01$) and the interaction effects between camera and grade (significant decrease, $p = 0.01$).
[l]GLM showed that cameras are associated with an increase in total injury crashes. This is based on the combination of the main effect of the camera (significant increase, $p = 0.00$) and the interaction effects between camera and grade (significant decrease, $p = 0.00$).

APPENDIX I

DETAILED CALCULATION OF FINANCIAL IMPACT

Notes and Assumptions

All costs associated with rear-end and angle crashes used in this report were extracted from an FHWA publication entitled *Crash Cost Estimates by Maximum Police-Reported Injury Severity within Selected Crash Geometries* (Council et al., 2005). In the publication, these costs are referred to as "mean comprehensive cost per crash," which include not only the monetary losses associated with medical care, other sources used, and lost work, but also non-monetary costs related to the reduction in the quality of life. All crash costs provided in the publication are grouped by crash geometry (type of crash), speed limit, and maximum injury severity. Throughout the current report, a fatal crash is considered an injury crash (i.e., fatalities are considered injuries). Crash costs in the FHWA publication are in 2001 dollars and were shown in Tables 5 and 6 in the publication.

Crash data (rear-end and angle) from Virginia jurisdictions are grouped into two categories: before camera (i.e., before installation of the cameras) and after camera. For "city" jurisdictions, crashes at the speed limit of less than 45 mph are in the dataset. For "county" jurisdictions, crashes at the speed limit of less than 45 mph and greater than 50 mph are in the dataset.

Methodology

The **c**omprehensive **c**rash **c**ost (benefit or loss) of red light camera enforcement for each jurisdiction for all intersections at which cameras were installed was calculated using five methods:

1. Crashes, Injury Severity Unknown
2. Crashes, No Injury
3. All Crashes (Injury Severity Unknown and No Injury)
4. Crashes Linking KABCO scale with Virginia's injury severity scale (levels 0 through 4)
5. Crashes Linking KABCO Scale with Virginia's Injury Severity Scale (Levels 0 through 4) Biased Toward Less Injury Severity.

Then, the results (benefit or loss) were compared. Each method, as shown by its title, calculates the cost of installing red light cameras based on certain severity of crashes. These methods were explained earlier in the report.

The comprehensive crash cost of cameras at a given intersection is represented as either a benefit (positive dollar amount), indicating a reduction in crashes (and thus crash costs) attributable to the presence of the cameras, or a loss (negative dollar amount), indicating an increase in crashes (and thus crash costs) attributable to the presence of the cameras). Further, the comprehensive crash cost for all five methods was calculated in two ways: normalized by time and normalized by ADT. In the normalized-by-time calculation, the impact of rear-end and angle crashes was determined by taking only time into consideration (i.e., the number of years with and without cameras at a specific intersection). Therefore, the total number of rear-end and angle crashes during the after or before camera installation period was pro-rated (normalized) based on the length of the period. In this calculation, the result (benefit or loss) is stated on a per year, per intersection basis. In the normalized-by-ADT calculation, the cost of rear-end and angle crashes for before and after camera periods was divided by the annual ADT. The results, therefore, are stated on a per *million* vehicles basis. This latter approach (normalized-by-ADT calculation) is more commonly used by highway engineers in traffic- related studies.

Computational Steps for Determining Comprehensive Crash Cost of Installing Cameras for City of Arlington in Crashes Where No Injury Was Recorded by Officer

In Step 1, all crashes involving injury were considered as “Injury, Severity Unknown.” In Step 2, crashes without an injury were considered as a “No Injury” type of crash. This example focuses solely on Step 1—the case of non-injury crashes. Tables I1 through I5 illustrate how the comprehensive crash cost of installing red light cameras for these non-injury crashes was calculated using the County of Arlington as an example.

Cameras were installed in four intersections in Arlington, as shown in Table I1. The numbers of rear-end and angle crashes are shown for the before and after camera periods. Since the before and after camera periods are of varying lengths among these intersections, the table should serve only as the basis of the calculation and should not be used to interpret the comprehensive crash cost of installing cameras. Tables I2 through I4 illustrate this impact.

Since the before and after camera periods were of varying lengths among these four intersections, the number of rear-end and angle crashes were adjusted to a per year basis for consistency in Table I2. For example, 5.43 (actually 5.428 rounded down to 5.43) representing the number of non-injury rear-end crashes for Route 50 & Manchester Street during the before camera period is derived by dividing 19, which is the number of rear-end crashes before camera installation, by 3.50, which is the number of years before camera installation, both shown in Table I1. In this way, the number of rear-end and angle crashes can be consistently compared among the four intersections. With respect to rear-end crashes, the number increased after camera installation except for Route 50 & Manchester Street, which decreased slightly. Rear-end crashes increased 551% at Route 50 & Fillmore Street. With respect to angle crashes, the volume of angle crashes increased after camera installation except at Route 1 & 27th Street, which showed no change.

Table I1. Number of Non-Injury Crashes and Number of Years Before and After Camera Installation

Intersection	Camera Installation Date	Period Duration in Years		Rear-end Crashes		Angle Crashes	
		Before[a]	After[b]	Before	After	Before	After
Lynn Street & Lee Highway (NB)	June 2000	2.42	4.58	2	5	12	32
Route 50 & Manchester Street (WB)	July 2001	3.50	3.50	19	17	11	12
Route 50 & Fillmore Street (EB)	Feb. 1999	1.08	5.92	1	30	2	12
Route 1 & 27th Street (SB)	July 2001	3.50	3.50	3	4	5	5

[a]The Before period began January 1, 1998, and continued until the month preceding camera installation.
[b]The After period began with the month of camera installation and continued until December 31, 2004.

Table I2. Number of Crashes Per Intersection-Year

Intersection	Rear-end		Angle	
	Before	After	Before	After
Lynn Street & Lee Highway (NB)	0.83	1.09	4.97	6.98
Route 50 & Manchester Street (WB)	5.43	4.86	3.14	3.43
Route 50 & Fillmore Street (EB)	0.92	5.07	1.85	2.03
Route 1 & 27th Street (SB)	0.86	1.14	1.43	1.43
Grand Total for Arlington	8.04	12.16	11.38	13.87

Table I3. Comprehensive Crash Cost ($ Per Intersection-Year) of Installing Cameras (Normalized by Time)

Intersection	Before Camera		After Camera		Benefit or Loss
	Rear-end[a]	Angle[b]	Rear-end[a]	Angle[b]	
Lynn Street & Lee Highway (NB)	$9,487	$43,066	$12,505	$60,553	-$20,506
Route 50 & Manchester Street (WB)	$62,228	$27,258	$55,677	$29,736	$4,072
Route 50 & Fillmore Street (EB)	$10,581	$16,012	$58,122	$17,590	-$49,120
Route 1 & 27th Street (SB)	$9,825	$12,390	$13,101	$12,390	-$3,275
Grand Total for Arlington	**$92,121**	**$98,726**	**$139,405**	**$120,270**	**-$68,828**

[a]Cost is $11,463 per non-injury rear-end crash that occurs at intersections with a speed limit of 45 mph or less.
[b]Cost is $8,673 per non-injury angle crash that occurs at intersections with a speed limit of 45 mph or less.

Table I4. Sum of Average Annual Traffic

Intersection	Sum of Average Daily Traffic[a]		Sum of Average Annual Traffic[b]	
	Before	After	Before	After
Lynn Street & Lee Highway (NB)	86,096	146,104	31,425,040	53,327,960
Route 50 & Manchester Street (WB)	199,500	214,500	72,817,500	78,292,500
Route 50 & Fillmore Street (EB)	56,240	350,760	20,527,600	128,027,400
Route 1 & 27th Street (SB)	71,500	98,500	26,097,500	35,952,500

[a]Determined by summing ADTs for each year. For example, a 2.42-year period with ADTs of 37,000 (1998), 37,000 (1999), and 28,800 (first 5 months of 2000) is summed as 37,000 + 37,000 + (0.42)*(28,800) = 86,096.
[b]Determined by multiplying the sum of average daily traffic by 365.

Table I5. Comprehensive Crash Cost ($ per Million Entering Vehicles) of Installing Cameras (Normalized by ADT)

Intersection	Before				After				Benefit or Loss
	Crashes per Million Vehicles[a]		Crash Cost		Crashes per Million Vehicles[a]		Crash Cost		
	Rear-End[b]	Angle[c]	Rear-End[b]	Angle[c]	Rear-End[b]	Angle[c]	Rear-End[b]	Angle[c]	
Lynn Street & Lee Highway (NB)	0.06	0.38	$730	$3,312	0.09	0.60	$1,075	$5,204	-$2,238
Route 50 & Manchester Street (WB)	0.26	0.15	$2,991	$1,310	0.22	0.15	$2,489	$1,329	$483
Route 50 & Fillmore Street (EB)	0.05	0.10	$558	$845	0.23	0.09	$2,686	$813	-$2,096
Route 1 & 27th Street (SB)	0.11	0.19	$1,318	$1,662	0.11	0.14	$1,275	$1,206	$498
Grand Total for Arlington	0.49	0.82	$5,597	$7,129	0.66	0.99	$7,525	$8,553	-$3,353

[a]Determined by dividing the number of crashes (e.g., 2) by the sum of average annual traffic (e.g., 31,425,040) and multiplying by 1 million (use of these values yields 0.06 crash per million entering vehicles).
[b]Cost is $11,463 per non-injury rear-end crash that occurs at intersections with a speed limit of 45 mph or less.
[c]Cost is $8,673 per non-injury angle crash that occurs at intersections with a speed limit of 45 mph or less.

In Table I3, the comprehensive crash cost is calculated for each intersection by multiplying the adjusted number of rear-end and angle crashes (as determined in Table I2) by the cost of each respective crash (rear-end or angle). For example, the cost of rear-end crashes before camera installation for Route 50 & Manchester Street is calculated as follows: 5.42857 x $11,463 per non-injury rear-end crash = $62,228. In the case of this intersection, the number of rear-end crashes per intersection year decreased (from 5.43 to 4.86) and the number of angles crashes increased slightly after camera installation (from 3.14 to 3.43). The monetized benefit of the decreased rear-end crashes per intersection year was greater than the monetized loss of the increased angle crashes per intersection year. Thus, the comprehensive crash cost is a net positive amount (a benefit). As can be seen from Table I3, however, the installation of cameras was associated with a net loss for the three other intersections under study in Arlington. These results were derived using the normalized-by-time calculation methodology.

To determine the comprehensive crash cost of camera installation using the normalized-by-ADT methodology, first the sum of ADT and the sum of annual average traffic had to be calculated, as shown in Table I4. Table I5 shows the cost of rear-end and angle crashes that occurred in each intersection in the study on a per million vehicle basis. By using this methodology, the impact of an intersection's traffic volume on the number of crashes in the intersection is taken into consideration. In essence, by using this methodology, the effect of traffic volume on the number of crashes (i.e., the higher the volume of traffic passing through an intersection, the greater the probability of crashes occurring at that intersection) can be considered. Therefore, the total number of crashes at each intersection for before and after camera installation periods was divided by the annual volume of traffic (Average Annual Traffic) and the result was multiplied by 1 million. The result is shown as "Crashes Per Million Vehicles." After multiplying the number of crashes per million vehicles by the cost of each respective crash (i.e., rear-end and angle), crash costs were derived. By comparing the crash costs of the before and after camera installation periods, the net benefit or the net loss may be determined. As shown in Table I5, in all except one intersection in Arlington, the installation of cameras was associated with a net loss for the jurisdiction. These results, as calculated based on the normalized-by-ADT methodology, are consistent with results computed based on the normalized-by-time methodology, shown in Table I3. (However, these results reflect only a few years after the installation of the cameras.)

Data Caveats

Step 2 in the methodology (crashes, injury severity unknown) was applied in a manner comparable to that shown above, and the sum of these steps gave Step 3 (all crashes, injury severity unknown and no injury). Steps 4 and 5 were used with the same dataset but took advantage of the officer's record of injury severity at the scene of the crash to give each injury crash a KABCO injury severity rating of K, A, B, or C. It should be noted that there were three anomalies in the dataset, however, when Steps 4 and 5 were applied.

- At the intersection of Arlington Boulevard and Jaguar Trail, prior to the camera's installation, the officer's indication of severity for one of the rear-end injury crashes was a type 6, which meant the officer did not record the severity of the injury crash and thus a KABCO value (such as K, A, B, or C) could not be determined as per

Steps 4 and 5. Thus, although that intersection had 10 injury rear-end crashes as per Step 2 in the methodology, it had only 9 injury rear-end crashes as per Steps 4 and 5 of the methodology.

- A similar situation occurred at the Lee Jackson/Fair Ridge intersection before camera installation: there was one type 6 injury severity. Thus, for that intersection, there were 18 injury rear-end crashes as per Step 2 in the methodology but only 17 injury rear-end crashes as per Steps 4 and 5 of the methodology.

- A similar situation occurred at the Route 28 & Green Trail/Old Mill intersection: after camera installation, there were six injury angle crashes as per Step 2 in the methodology, but only five angle injury crashes as per Steps 4 and 5 of the methodology.

REFERENCE

Council, F., Zaloshnja, E., Miller, T., and Persaud, B. *Crash Cost Estimates by Maximum Police-Reported Injury Severity within Selected Crash Geometries.* FHWA-HRT-05-051. Federal Highway Administration, McLean, VA, 2005. http://www.tfhrc.gov/safety/pubs/05051/05051.pdf. Accessed April 28, 2006.

APPENDIX J

SUMMARY OF AVAILABLE VIRGINIA CODES DATA

From 2001 through 2002, a total of 3,346 crashes occurred at selected signalized intersections in Northern Virginia. These intersections consisted of those where a red light camera was installed at some point from 1998 through 2004 inclusive and comparable intersections where no such camera was installed. Based on these 3,346 crashes, VHI, Inc. provided the Virginia Transportation Research Council with detailed injury data for the crashes for which such injury data were available. The data from VHI, Inc., are in three data files: (1) patients transported by emergency medical services (EMS), (2) patients admitted to a hospital after being transported by EMS, and (3) patients admitted directly to the hospital.

As indicated in Table J1, about one third of the total (1,256 crashes) were indicated as an "injury" crash by the law enforcement officer at the scene and thus recorded as an injury crash by Virginia's Department of Motor Vehicles (DMV). However, although the officer recorded these as having an injury, detailed data are not available for all crashes. For *approximately* one fourth of these crashes (287), there is at least one record showing that an injured person was transported by EMS to a hospital. There can be more than one injury—and hence more than one record—per crash. For example, although there are 287 *crashes* shown in the Crash to EMS file, there are 377 *records* shown in the file, since some crashes had more than one person transported by EMS.

Although the Crash to EMS data file did not contain detailed injury information, details are available in the last two files shown in Table J1: those patients who were taken directly from the crash and admitted to the hospital (74 crashes) and those patients who were admitted to the hospital after being transported by EMS (29 crashes). These latter two datasets, shown in Table J1, are almost mutually exclusive: of the 103 crashes shown therein, only 7 appear in both datasets. Thus, based on the last two rows of Table J1, there was a hospital admission for 96 crashes.

Table J1. Summary of Crashes for 2001 and 2002

Data Source	2001 Crashes	2002 Crashes	Total Crashes	Total Records
Total Crashes (DMV)	1,708	1,638	3,346	N/A
PDO Crashes (DMV)	1,059	1,031	2,090	N/A
Injury Crashes (DMV)	649	607	1,256	N/A
Crash to EMS (VHI)	214	73	287	377
Crash to Hospital (VHI)	49	25	74	78
EMS to Hospital (VHI)	14	15	29	30