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Reconsidering the Impact of Access Spacing on Crash Risk

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16. Abstract:

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A comprehensive literature review was conducted, examining the directionality and magnitude of the safety impacts of access spacing, the selection of exposure indicators, and the statistical methods employed. An experiment was designed to compare the crash outcomes of 33 control sites with large access spacing and 33 experimental sites with short access spacing. Random effects negative binomial (RENB) models were developed and identified as the appropriate approach to explore the safety impact of access spacing while accounting for exposure indicators and other factors such as the number of turn lanes and sight obstructions.

Results indicated that shorter spacing significantly increased total crashes but had no significant effect on severe crashes. Moreover, it was found that violating VDOT's minimum access spacing standards would increase total crashes by 64.8%. Based on these findings, the study recommends that VDOT should continue to maintain its current minimum spacing standards for accesses. Adhering to these standards can help prevent escalating crash costs in the long term.

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ABSTRACT

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INTRODUCTION

State agencies develop access management regulations that provide systematic control of the location, spacing, design, and operations of access points (including intersections, entrances, median opening, and ramps/interchanges) to ensure the safety and efficiency of roadway systems. For instance, Section 33.2-245 of the Code of Virginia on "Comprehensive highway access management standards" requires VDOT to implement access management regulations and standards for state-maintained roadways. The spacing of access points is one of the most critical elements in access management. *VDOT Access Management Design Standards for Entrances and Intersections* (Appendix F of the *VDOT Road Design Manual* (VDOT, 2011)) shows standards on the spacing of access points. VDOT provides different standards governing access management for roadways with distinct functional classifications (e.g., principal arterials, minor arterials, collectors, and local streets). For example, principal arterials are meant to provide high mobility and thus a greater minimum access spacing should be allowed in contrast to other functional types.

It is important to ensure that these access standards (e.g., the spacing between access points and the number of access points per mile) are occasionally updated to reflect the state-of-the-art research findings that draw on better quality data and improved analytical methods. In this context, a long-held hypothesis in the access management arena is that smaller access spacing results in higher crash risk. For example, according to NCHRP Report 420 (Gluck et al. 1999), crash rates were found to increase by 40% and 150% along specific roadways in Georgia and Florida, respectively, if the number of traffic signals per mile doubled.

The research problem is the uncertainty of whether the hypothesis – that smaller access spacing increases crash risk – remains valid after properly controlling for the traffic exposure on both mainline and accesses. Accordingly, a robust approach is needed to test this hypothesis while controlling for traffic exposure. The outcomes of this research will provide VDOT with valuable insights to enhance access management practices, potentially leading to improved safety and operational efficiency on the roadways.

PURPOSE AND SCOPE

This research aims to determine if access spacing affects crash risk (for total crashes and severe injury crashes), to quantify the magnitude of those impacts (if applicable), and to identify other confounding factors that may also influence crash risk when access management is considered.

This research is composed of two phases. In Phase I, conceptual structures were developed for understanding crash causation on corridors with closely spaced access points, based on a thorough review of existing literature and an analysis of crash records. It was found that shorter access spacing was associated with more rear-end crashes and crashes caused by following too close, which were likely attributed to the high variance in speed. These results provided evidence supporting the conceptual structure that shorter access spacing increases the speed variance of mainline traffic and consequently crash risk. A memorandum summarizing Phase I is included as a supplementary file to this report. Phase II, the subject of this report, builds upon Phase I by developing methods to articulate the corresponding conceptual structure regarding how access spacing influences crash risk. The research objectives of Phase II include:

- Conduct a comprehensive literature review on the impact of access spacing on crash risk.

- Design an experiment that compares sites with large access spacing (control group) to sites with short access spacing (experimental group), ensuring that most other factors remain consistent between the two groups.

- Develop statistical methods to investigate the effect of access spacing on crash risk (between-group effect), accounting for traffic exposure (e.g., mainline and access volumes), the access type (e.g., unsignalized intersection, full access, and partial access), and other contributing factors (e.g., number of turn lanes, sight obstruction).

- Examine the VDOT's access spacing standards and recommend adjustments if supporting evidence is provided.

In terms of scope, the study focuses on unsignalized access types, since safety performance of signalized intersections is largely influenced by the signal timing configuration (e.g., number of phases, yellow interval, all-red interval). All unsignalized access points selected for analysis are located on principal arterials, minor arterials, and collectors, where access management is more critical to operation and safety. Limited access highways (e.g., interstate) are excluded given that the primary focus of this research is not interchange/ramp spacing. Local streets are also excluded given the fewer access-related crashes because of the lower exposure.

METHODS

The following tasks were conducted to achieve the research objectives:

- Literature Review
- Experimental Design and Site Selection
- Data Collection and Assembly
- Assess Impacts of Access Spacing
- Examine VDOT's Access Management Standards

Literature Review

The research team conducted a comprehensive literature review on safety impacts of access spacing. This review focused on the reported facts documented in research studies, technical reports, or other published materials by agencies. The synthesis effort included the following key components:

- Summarized key findings regarding the directionality and magnitude of the safety impacts of access spacing.
- Explored the selection of exposure indicators (e.g., access volume, mainline volume, and vehicle mile traveled) and the characterization of access spacing (e.g., average spacing, the nearest spacing, and access density), along with other explanatory variables (e.g., presence of shoulder and speed limit) used for modeling.
- Identified statistical methods used for safety modeling.

Experimental Design and Site Selection

The focus of this task was to design an experiment to compare the safety outcomes of control sites with large access spacing and experimental sites with short access spacing. As a recommendation of Phase I, access pairs were selected as units of analysis (e.g., in Figure 1, both control and experimental sites are access pairs). The research team selected access pairs as the unit of analysis for two reasons: 1) the impact of access spacing on safety can be directly analyzed; and 2) it is relatively easier to match control and experimental sites for a pair of accesses than for segments with multiple accesses. Commercial driveways were treated as access points due to their considerable traffic demand, while residential driveways were not considered as access points. Phase II focuses on three unsignalized access types, including:

- Type 1: 4-legged intersection (Equivalent to unsignalized intersection/full crossover in *VDOT Road Design Manual*)
- Type 2: 3-legged intersection with full access (Equivalent to full access in *VDOT Road Design Manual*)
- Type 3: 3-legged intersection with partial access, limited to right-in/right-out movements (Equivalent to partial access in *VDOT Road Design Manual*)

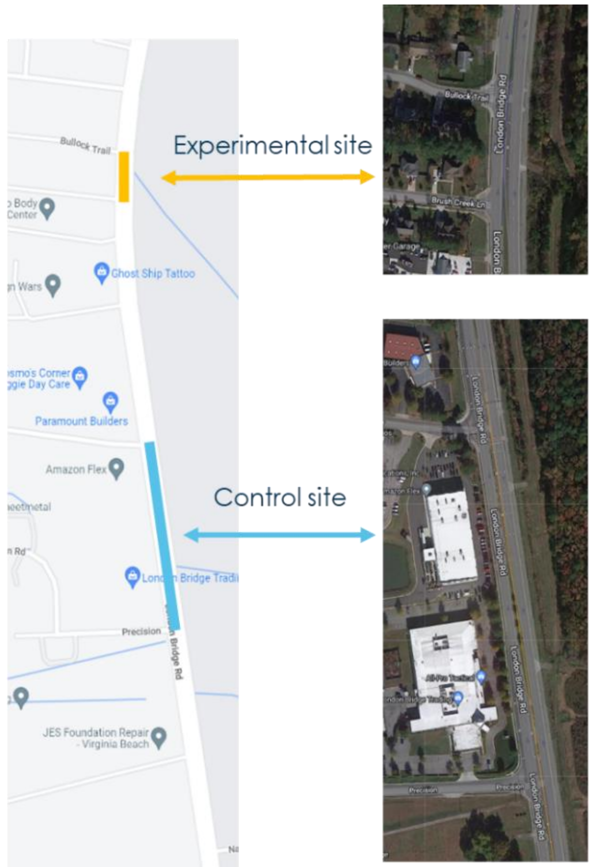


Figure 1. An Example of Control and Experimental Sites, Map data © 2024 Google

Other access types listed in the *VDOT Road Design Manual* (VDOT, 2011) such as directional median crossovers were excluded from analysis. The reason for excluding directional median crossovers is that they are far less common than the other access types and have a unique conflicting pattern (nine potential conflict points).

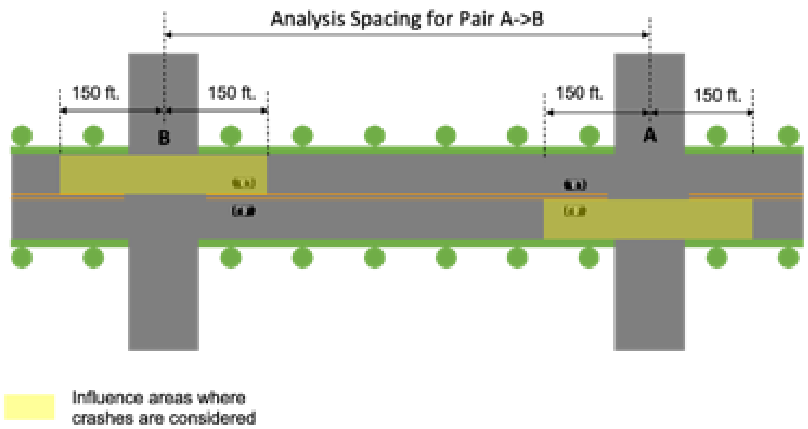
In the experiment, the research team selected access pairs with large access spacing as control sites and access pairs with short access spacing as experimental sites. Each control site was matched with an adjacent experimental site of the same access type on the same corridor, as illustrated in Figure 1. This matching ensured that the control and experiments sites were similar in terms of mainline traffic volume, median type, speed limit, and on-street parking, while being identical in access type. By controlling for these variables, this reduced the sample size needed for reliable statistical inference. Other factors that were difficult to control in the experimental design, such as access volume, number of turn lanes, etc., were included as covariates in the statistical models.

Due to resource constraints, the research team proposed to select 66 sites (33 control sites and 33 experimental sites) in Hampton Roads and Richmond, where a variety of access types and built environments could be found. A minimum sample size of 30 is typically required to generate reliable statistical inference. The proposed 33 pairs of sites provide a 10% buffer above the minimum, ensuring that the study remains robust even if some data are rendered unusable due to unforeseen circumstances.

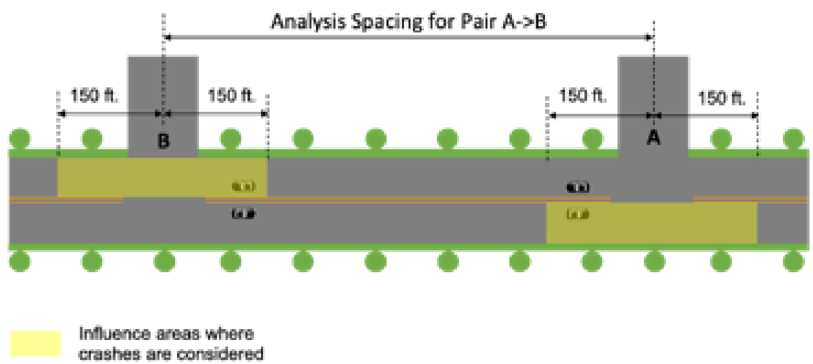
Data Collection and Assembly

Crash Data

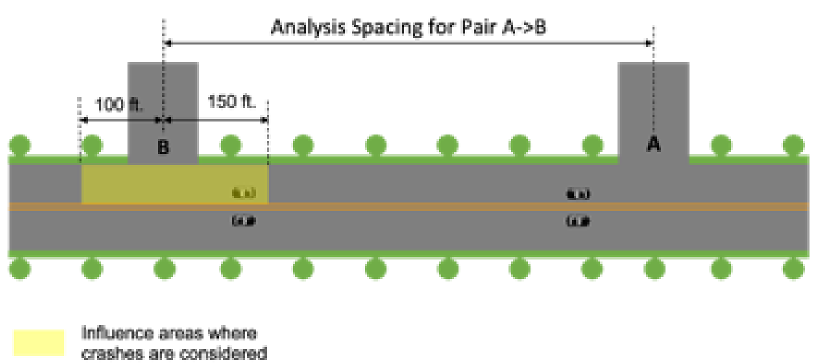
For each access pair, only crashes in its influence area were collected for analysis. The influence area defined for each access type is illustrated in Figure 2. A previous VTRC study (Flintsch et al., 2020) has defined the ranges of influence areas by access type. The influence area of a partial access ranges from 150 feet upstream to 100 feet downstream; while the



(a) Type 1: A pair of 4-legged intersections without median (or with median)



(b) Type 2: A pair of 3-legged intersections with full access without median (or with median)



(c) Type 3: A pair of 3-legged intersections with partial access without median (or with median)

Figure 2. Targeted Access Types and Influence Areas

influence area of a full access ranges from 150 feet upstream to 150 feet downstream. According to the conceptual structure proposed in Phase I – "Shorter access spacing increases the speed variance of mainline traffic and consequently elevates crash risk" – and discussions with the technical review panel, short access spacing primarily affects the downstream access point in each traffic direction. For Type 1 and Type 2 accesses, the influence area is bidirectional as shown in Figure 2 (a-b). For Type 3 accesses, the influence area is unidirectional as shown in Figure 2 (c) since the traffic entering and exiting a partial access will not interrupt the traffic operation in the opposite direction.

Traffic Volume

Two sources of traffic volume data were considered: field observation and StreetLight Insight ® (StreetLight 2023). Due to resource constraints, field observations are limited to a small number of sites and time periods. This limited observation period can result in significant variability in the data, which may not accurately represent typical traffic conditions. In contrast, StreetLight data offers broad coverage in both time and space, but its accuracy needs validation. Field data, including access volumes and mainline volumes, were collected for a few selected sites and used to validate the StreetLight data. If the validation would prove successful, StreetLight data would be used for further analysis.

Other Characteristics

The research team additionally gathered data on road functional classification, speed limits, lane configuration, and sight obstructions to facilitate further analysis. Functional classification and speed limits were sourced from VDOT (2023) and VDOT (2022), respectively. Google Maps was utilized to identify lane configuration, and sight obstructions.

More specifically, four turn-lane characteristics were considered as illustrated in Figure 3, including the number of left-turn lanes for the intersection A, the number of right-turn lanes for the intersection A, the number of left-turn lanes for the intersection B, the number of right-turn lanes for the intersection B. The total number of turn lanes were also computed.

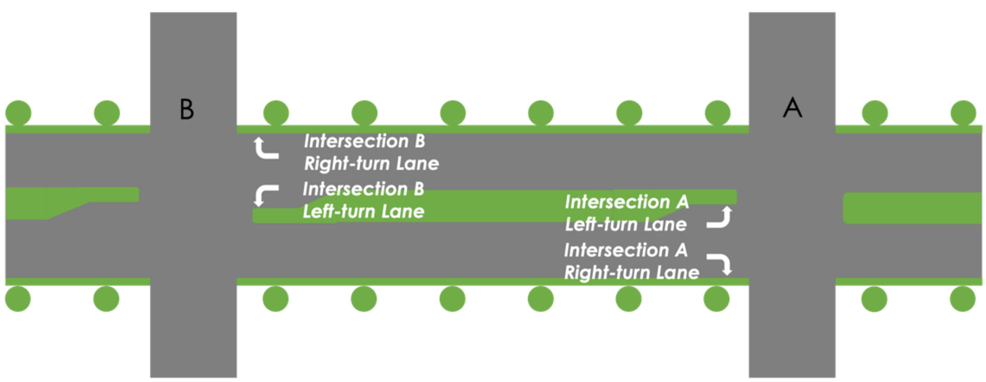


Figure 3. Four Turn-Lane Characteristics

Sight obstructions can stem from both fixed objects (e.g., trees, buildings) and movable ones like parked vehicles. This study considered both types of obstructions. Sight distance triangles were constructed for selected sites to assess the presence of obstructions. If fixed objects or parking areas were present within these sight triangles, the site was identified as having fixed-object-related obstruction or parking-related obstruction. Figure 4 illustrates the sight triangle for a 4-legged stop-controlled intersection. For this study, Stopping Sight Distance (SSD) was used to construct sight triangles due to the safety focus. The SSDs corresponding to different speed limits are listed in Table 1. When the median was wide enough to serve as a refuge for vehicles, only the left sight triangle was examined.

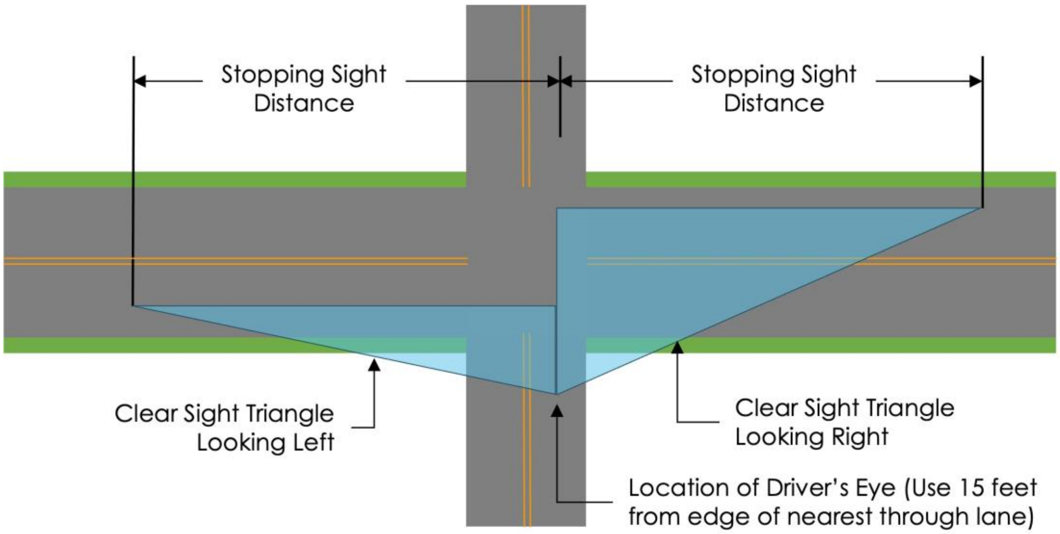


Figure 4. Sight Distance Triangles for 4-Leg Stop-controlled Intersections (Modified based on Figure 3 from FHWA (2011))

Table 1. Stopping Sight Distances (SSDs) according to Different Speed Limits (AASHTO 2018)

Speed (mph) *	Stopping Sight Distance (ft.)
25	155
30	200
35	250
40	305
45	360
50	425
55	495

Assess Impacts of Access Spacing on Crashes

This task focused on developing statistically rigorous methods to investigate the effect of access spacing on crash risk while controlling for traffic exposure, access type, and other explanatory variables. It was found in Phase I that there were excessive rear-end crashes on mainlines with shorter access spacing, which generally led to minor injuries. Thus, the research team not only investigated the impact of accessing spacing on the total crash count but also on crash severity. Total crash counts and severe crash counts (including fatal injuries and severe injuries) were compared between the control and experimental groups. The two-sided paired t-test and the random effects negative binomial (RENB) model were used to evaluate the impact of access spacing on crash occurrence.

Method 1: Two-Sided Paired T-Test

The hypotheses for the two-sided paired t-test are formulated as follows:

- H_0: The mean difference in crash counts of experiment and control groups is equal to zero; and
- H_1: The mean difference in crash counts of experiment and control groups is not equal to zero.

The test statistic of the paired t-test is given by:

$$t = \frac{\sum d}{\sqrt{\frac{n(\sum d^2) - (\sum d)^2}{n-1}}} \tag{1}$$

where d is the difference of crash counts in each pair of sites; n is the tested number of the paired experiment and control sites.

Method 2: Random Effects Negative Binomial (RENB) Model

For the RENB model, the model formulation is:

$$y_i \sim Possion(\lambda_i)$$
$$ln(\lambda_i) = \beta_0 + \beta_E E + \beta_L \, log(Length) + P_j + \varepsilon_i \tag{2}$$

where, y_i is the count of a target crash type at site i; λ_i is the expectation of y_i; E is the binary group indicator (1 for experimental site, and 0 for control site); $\boldsymbol{X}$ is a vector of covariates such as access volume, lane use type, number of lanes in access, etc.; $\boldsymbol{\beta_X}$ is a vector of coefficients for these covariates; β_0 is the intercept; β_E is the coefficient of E; P_j is the pair-specific random effect, while $j = 1, 2, \dots, 30$; and ε_i is the error term.

The RENB model can better accommodate over-dispersed crash counts and flexibly accounts for the effects of road length. P_j is used to pair sites and to capture the effect of pair-specific factors such as mainline volume, speed limit, etc. The coefficient of E (β_E) captures the effect of small access spacing on crash risk, which is the primary focus of our analysis. The research team also explored the selection of appropriate exposure indicators, including the consideration of using access volume and mainline volume separately versus using the product of access and mainline volumes. Models incorporating different exposure indicators were compared and analyzed.

Examine VDOT's Access Management Standards

This task focused on examining VDOT's access management standards on minimum spacing, as shown in Table 2. The determination of minimum spacing required both the functional classification and design speed of the roadway. Functional classification data was sourced from VDOT (2023), while speed limits, used as a proxy for design speed, were obtained from VDOT (2022). The research team selected access pairs where the control site had spacing greater than the minimum required distance, and the experimental site had spacing below the minimum. For example, consider the selected access pair of C2 and E2 in Figure 5. Providence Road in Chesapeake is classified as a Minor Arterial with a speed limit of 40 mph. According to Table 2, the minimum access spacing for a Type 1 unsignalized intersection is 660 feet. The actual spacing at control site C2 was 1,193 feet, exceeding the standard, while the spacing at experimental site E2 was 425 feet, falling short of the minimum required distance of 660 feet.

Table 2. Standards on Minimum Spacing (VDOT, 2011)

Functional Classification	Design Speed	Minimum Spacing (Distance) in Feet		
		Type 1 (Unsignalized / Full Crossover)	Type 2 (Full Access / Directional Crossover)	Type 3 (Partial Access)
Principal Arterial	≤ 30 mph	800	440	250
	35 to 45 mph	1,050	565	305
	≥ 50 mph	1,320	750	495
Minor Arterial	≤ 30 mph	660	355	200
	35 to 45 mph	660	470	250
	≥ 50 mph	1,050	555	425
Collector	≤ 30 mph	440	225	200
	35 to 45 mph	440	335	250
	≥ 50 mph	660	445	360

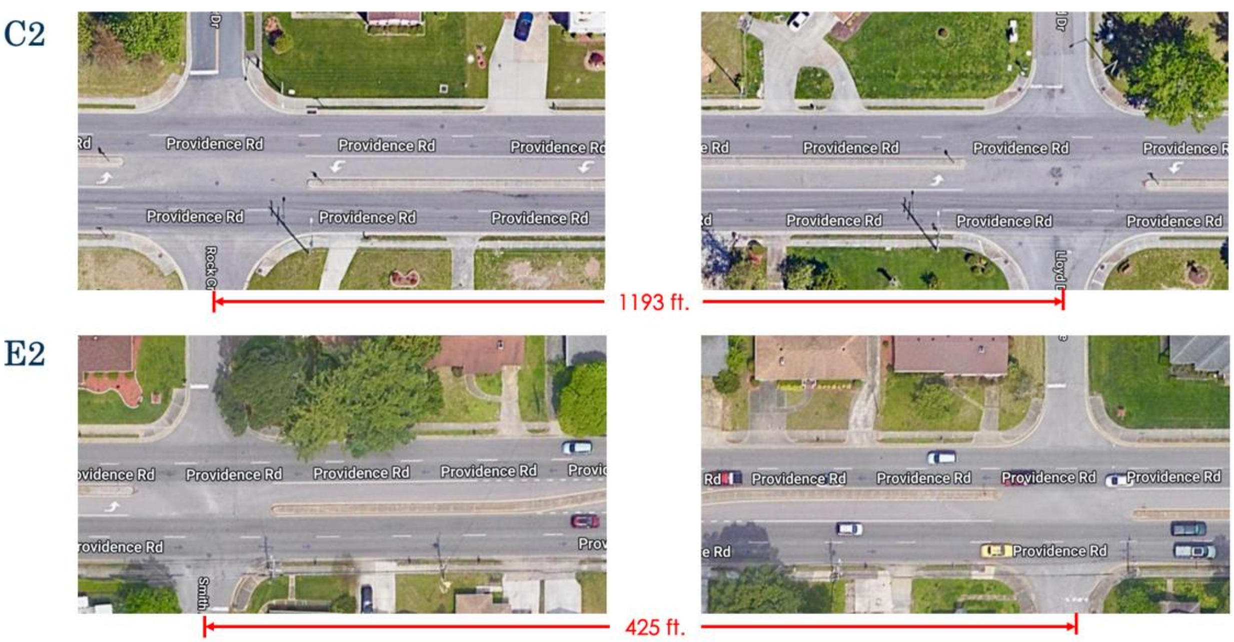


Figure 5. Control Site 2 (C2) and Experimental Site 2 (E2), Map data © 2024 Google

The RENB models were developed using the data from the selected access pairs with the spacing of each control site over the VDOT's minimum spacing standards and the spacing of the experimental site below the minimum standards. The coefficient of E (β_E) captures the impact of violating the VDOT's minimum spacing standards on crash risk.

RESULTS

Literature Review

This section provides a review of studies on the impacts of access spacing on crash risk, including the analytical methods applied and how to characterize access spacing.

Impact of Access Spacing on Crash Risk

There are many studies that examined the relationship between access spacing and crash risk. A previous VTRC study (Flintsch et al., 2020) found "impacts of access point spacing (in particular) on safety were mixed and depended on how the analysis unit was defined." As stated in the TRB Access Management Manual (Williams et al., 2014), most studies found that the number of access points was positively associated with crash risk. A meta-analysis of 27 access spacing studies until 2017 found that the average number of crashes increased by 4% because of one additional access point per kilometer (0.62 miles) after controlling for traffic volume (Elvik, 2017). NCHRP Report 420 (Gluck et al., 1999) synthesized a number of studies from the 1950s to the 1990s and provided a comprehensive view of the impacts of access spacing on safety for various access types. An FHWA report (Gross et al., 2018) used over 600 miles of detailed corridor data from four different regions in the United States and developed crash frequency models for various land uses and crash types considering the effects of the spacing of intersection, driveways, and median openings. Sarasua et al. (2015) showed that raising driveway spacing from 150 to 200 feet was expected to reduce crashes by 2%. Studies (Xie et al., 2013; Xie et al., 2014) by the research team found an increase in the spacing of signalized intersections would reduce the crash risk. A recent study (Hamzeie et al., 2019) found that for both two-lane and multilane highways, crashes would increase consistently as the average spacing of access points along road segments decreased.

In summary, multiple studies (e.g., Hamzeie et al., 2019; Xie et al., 2013) found that shorter spacing between access points such as intersections and driveways was generally associated with increased crash risk, although the magnitude of this effect could vary depending on analysis methods. However, most of the previous studies shown in Table 3 did not fully account for the traffic exposure, especially access volumes, due to the data availability obstacles. For instance, Gross et al. (2018) claimed the lack of volumes on cross streets and driveways as one of the key limitations.

Characterizing the Access Spacing

There are a variety of ways to characterize the access spacing, such as the number of access points (e.g., Gross et al., 2018), average spacing (e.g., Hamzeie et al., 2019), the nearest distance between accesses (e.g., Xie et al., 2013), and the most widely used one – access density (e.g., Elvik, 2017). Previous studies suggested that researchers used different definitions of access density. While the generic definition for access density was the number of access points divided by the length of the roadway segment, some researchers suggested using weighted metrics given the varying impacts of different access types on safety. For instance, Saxena (2010) defined access density as the weighted sum of the number of diverging, merging, crossing, and weaving conflicts of different access points with respect to the length of a roadway segment. Another study defined access density as the sum of access weights (that reflect the traffic speed variation) of different access points along a corridor divided by the length of the corridor (Huang et al., 2014). This metric was found to have a higher correlation with crash risk compared to traditional access density metrics for a sample street in Florida. More comparisons and details of research are listed in Table 3.

In summary, researchers employed various methods to characterize access spacing, such as counting the number of access points, calculating average spacing, measuring the nearest distance between accesses, and using the commonly applied access density – whose definitions vary among studies. These differing metrics can affect study results. To address this variability, this study avoided directly characterizing access spacing, but instead compared access pairs with large spacing to those with short spacing. For more details on this approach, refer to the section on Experimental Design and Site Selection.

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Table 3. Summary of models for impacts of access spacing on crash risk

Study	**Dependent variables**	**Experimental variables**	**Effect of experimental variable**	**Exposure indicator**	**Covariates**	**Model**	**Data**	**Region**
Gross et al. (2018)	Crash frequency (All types of crashes in three land use scenarios)	Maximum spacing of signalized intersections, Minimal spacing of signalized intersections	Negative	AADT (for the corridor)	• Adjacent land use • Driveway Density • Median type • Number of median openings • Signalized intersection density etc.	Linear regression model	Signalized intersections and unsignalized intersections	North Carolina, Northern, California, Southern California, Minnesota
Hamzeie et al. (2019)	Crash frequency (Crash per mile per year on highways)	Access spacing of different ranges	Negative	Log AADT (for the corridor)	• Access spacing with different lengths • Divided highway • Number of at-grade signalized intersections etc.	Random effect negative binomial regression model	Signalized or stop-controlled intersections	Iowa
Xie et al. (2013)	Crash frequency	Distance to the nearest intersection	Negative	ADT (for the intersection)	• Proximity of intersections • Intersection type • Ratio of turning lanes • Average Speed etc.	Bayesian hierarchical negative binomial model	Signalized intersections	Shanghai
Elvik (2017)	Crash rate (Injury crashes per million vehicle kilometers)	Access point density	Positive	Ln AADT (for the corridor)	• Access point number per different kilometers of road	Random effects meta-regression models	Signalized intersections and unsignalized intersections	Norway
Huang et al. (2014)	Crash rate (Crashes per million vehicle miles traveled)	Sum of access weights of different access points on one road divided by the length of the roadway segment	Positive	AADT (for the corridor)	• Access density	Linear regression model	Signalized intersections and unsignalized intersections	Florida

Study	Dependent variables	Experimental variables	Effect of experimental variable	Exposure indicator	Covariates	Model	Data	Region
Mauga and Kaseko (2010)	Crash rate (Rates in midblock of different crash types and different levels of severity)	Signal spacing	Negative	AADT (for the corridor per lane)	• Density of median openings (per mile) • Density of crossroads (per mile) • Density of driveways (per mile) • Speed limit (mph)	Multivariate regression models	Midblock sections	Nevada
Flintsch et al. (2020)	Crash frequency (Crashes in analysis unit) Crash rate (Crashes million vehicle miles traveled)	Access spacing groups	Negative	Log ADT (for the corridor)	• Access volume • Access control type • Number of low-residential driveways • Land use • Speed limit	ANOVA, Poisson and negative binomial mixed regression models	Unsignalized intersections	Virginia
Abdel-Aty and Wang (2006)	Crash frequency	Distance to the nearest access point for the major roadway at the intersection	Negative	Log ADT (for the intersection per lane)	• Number of lanes • Intersection configuration • Speed limit • Intersection location types • Logarithm of distance to the nearest signalized intersection along corridor etc.	Generalized estimating equations and negative binomial models	Signalized intersections	Florida
Vaiana et al. (2021)	Crash frequency Crash severity	Private access points per kilometer	Positive	AADT (for the corridor)	• Roadway • Sidewalk • Private access points • Pavement • Traffic signs • Road markings etc.	Linear regression models, Non-linear regression models, etc.	Signalized intersections and unsignalized intersections	Southern Italy

Experimental Design and Site Selection

The research team selected 33 control sites with large access spacing and matched them with 33 experimental sites with short access spacing. The selected pairs of sites are mostly located in the Hampton Roads and Richmond areas, as shown in Figure 6. Details regarding site selection are available at "Accessing Spacing Sites", created with Google My Maps (Xie, 2024).

Control group sites are labeled with a "C" followed by an ordered number and the type of access spacing, while experimental group sites are labeled similarly with an "E." For example, C1(c) indicates a 3-legged intersection with partial access in the control group, while E2(b) represents a 3-legged intersection with full access in the experimental group. Satellite images of the selected pairs and the corresponding spacing distances are provided in Appendix A.

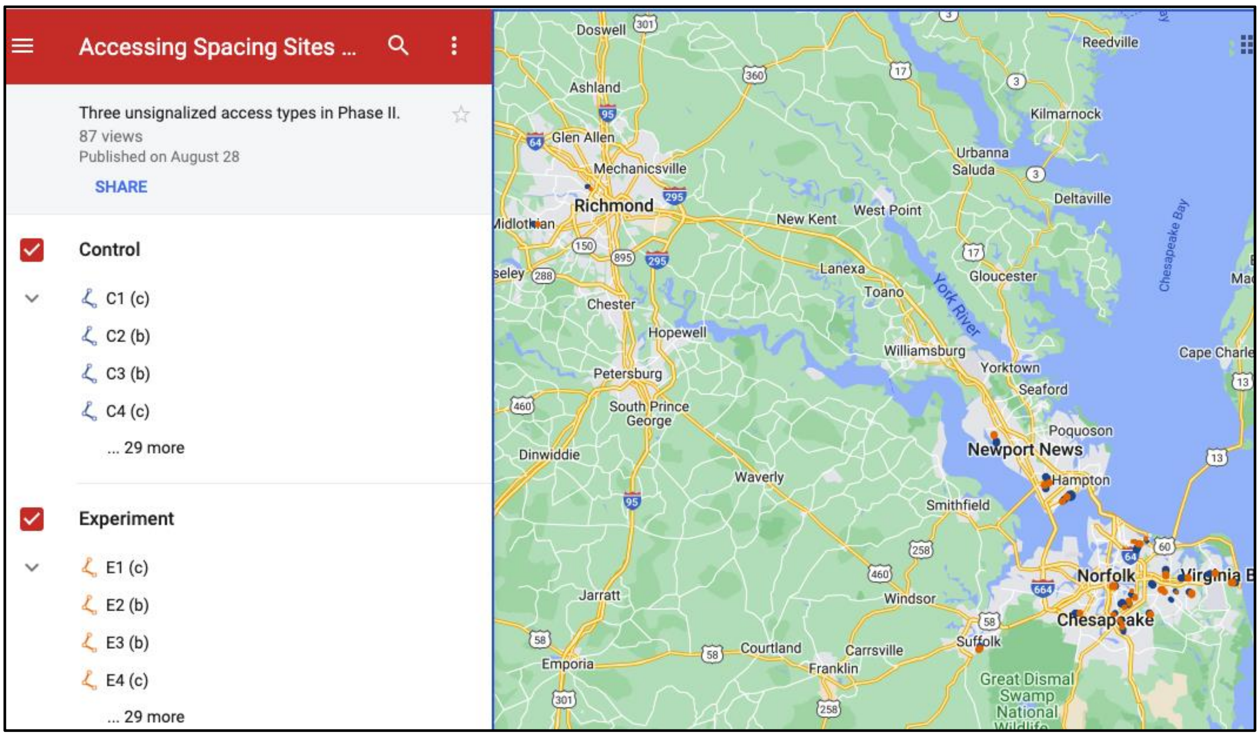


Figure 6. Google My Maps of Selected Sites, Map data © 2024 Google

The distributions of access spacing for the control and experimental sites are presented in Figure 7. With a significance level of 95%, the test statistics $t(32) = -10.4$, and the p-value < 0.001, results of the paired-t test indicated that there was a statistically significant difference between 0 and mean differences of the experimental and control group's spacing (mean = -411.6, standard deviation = 226.5).

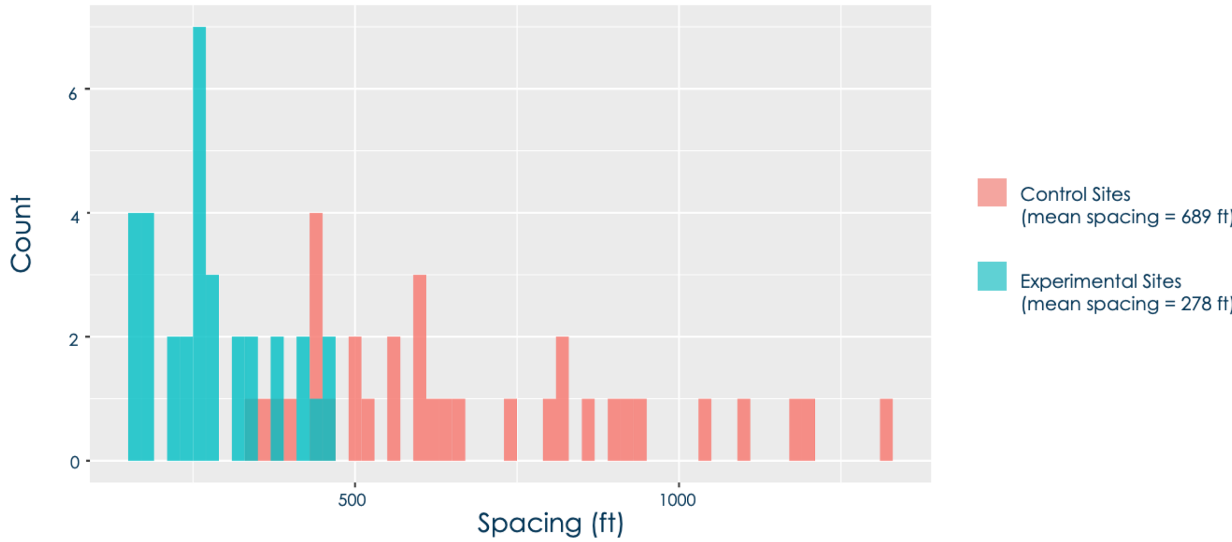


Figure 7. Distributions of Access Spacing for the Control and Experimental Sites

Data Collection and Assembly

Crash Data

The research team collected total crash counts and severe crash counts for selected sites from 1/1/2015 to 6/30/2023. Severe crashes were defined as those resulting in fatal and incapacitating injuries. Virginia Crash Map (VDOT 2024) and VDOT Crash Analysis Tool (VDOT 2024) were utilized to extract crash records within influence areas (defined in Figure 2.).

A summary of crash data of the control and experimental sites is presented in Table 4. The mean total crash count at the experimental sites is 3.12, which is higher than the mean total crash count at the control sites, which is 2.21. However, the experimental sites have a slightly lower count of severe crashes compared to the control sites.

Table 4. Summary of Crash Data

	Control Sites		Experimental Sites	
	Mean	**Standard Deviation**	**Mean**	**Standard Deviation**
Total Crashes	2.21	2.79	3.12	3.08
Severe Crashes	0.15	0.44	0.12	0.33

Traffic Volume

The research team observed traffic volumes by movement for 12 intersections across three pairs of sites—C2 & E2, C6 & E6, and C11 & E11—during the weekday PM peak traffic period (16:00 – 18:00) from April to June 2023. Of the 12 intersections, eight had data recorded for one day, while the remaining four had data for two days. Simultaneously, access and corridor volumes for these intersections were obtained from StreetLight for the same weekday PM peak period, but from an earlier data range of April 30 to October 31, 2019.

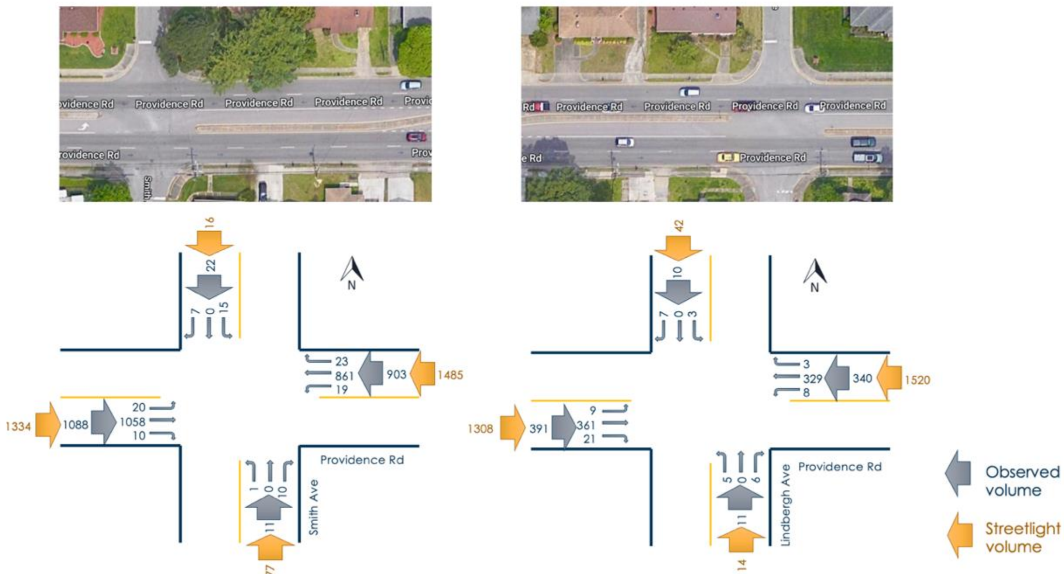
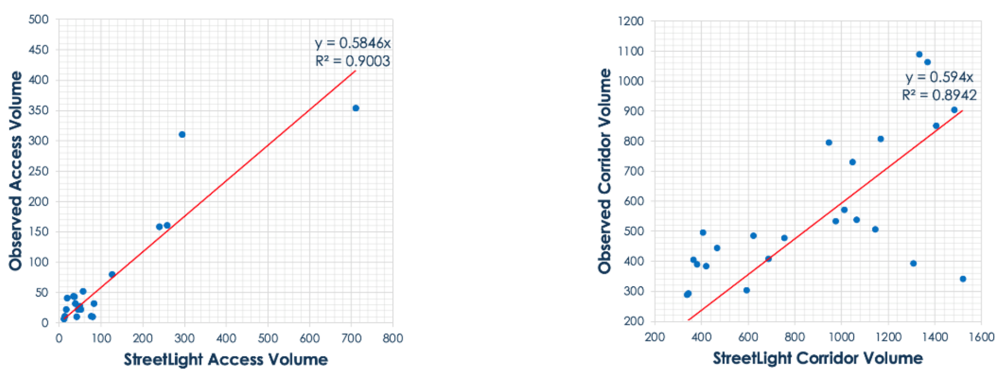


Figure 8. Observed Volumes vs StreetLight Volumes for Site E2, Map data © 2024 Google

The team compared the observed volumes with the StreetLight volumes for these sites. For example, Figure 8 shows the volume data for site E2 collected by the two methods, represented in different colors. The gray bars show vehicle counts observed by the same investigator on different weekdays, while the orange bars represent predicted volumes from StreetLight segment analysis. Both types of data include access and corridor volumes. It is worth noting that for the intersection of Providence Road and Lindbergh Avenue, there was a significant discrepancy in mainline volumes compared to the intersection of Providence Road and Smith Avenue. This difference is attributed to the fact that the vehicle counts for the Providence Road and Lindbergh Avenue intersection were collected during the local public schools' spring break. A complete comparison of StreetLight volumes and observed volumes for multiple sites is provided in Appendix B.



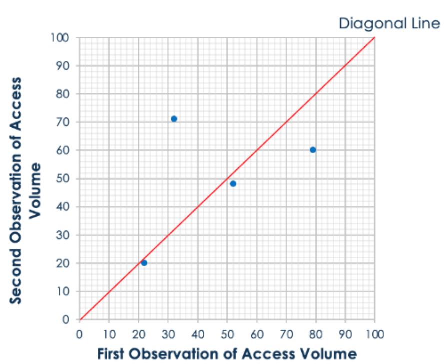
Parameter	Value
Pearson correlation coefficient (r)	0.9216
P-value	<0.0001
Sample size (n)	20
Statistic	10.0737

Parameter	Value
Pearson correlation coefficient (r)	0.6596
P-value	0.000454
Sample size (n)	24
Statistic	4.1162

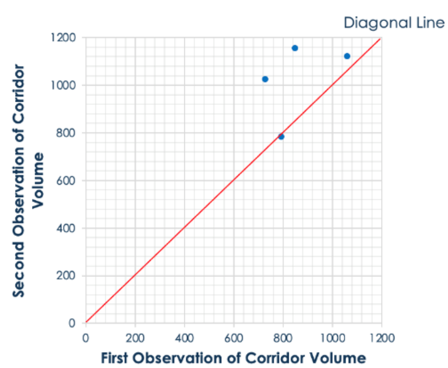
Figure 9. Comparison of StreetLight Volumes and Observed Volumes

Pearson correlation tests were conducted to compare the traffic volumes from StreetLight with those from field observations, with results shown in Figure 9. The tests showed a significant correlation between the two data sources, with a Pearson correlation coefficient of 0.9216 for access volumes and 0.6596 for corridor volumes. Although StreetLight volumes were generally higher than the observed volumes, the strong correlations indicated the validity of using StreetLight data for safety modeling. Additionally, linear regression models were used to estimate observed access volumes based on StreetLight data, achieving satisfactory accuracy.

Pearson correlation tests were also applied to assess day-to-day variations in observed volumes, as shown in Figure 10. The results showed that the correlation coefficients between observed volumes on different days were 0.4496 for access volumes and 0.4697 for corridor volumes. The correlation between StreetLight volumes and observed volumes (0.9216 for access volume or 0.6596 for corridor volumes) was either higher than or comparable to the correlation between observed volumes on different days (0.4496 for access volumes or 0.4697 for corridor volumes). This suggested that StreetLight data was a better option for further analysis, considering the broader coverage of the StreetLight data and the considerable large day-to-day variation in observed volumes. Thus, the research team used StreetLight to obtain traffic volumes for 66 sites over a one-year period, from May 1, 2021, to April 30, 2022. The StreetLight data used for analysis covered all days of the week, from Monday to Sunday, spanning 24 hours each day. This comprehensive dataset enabled a more robust analysis and could be better associated with all crashes occurring throughout the day.



Parameter	Value
Pearson correlation coefficient (r)	0.4496
P-value	0.00066
Sample size (n)	4
Statistic	17.1317



Parameter	Value
Pearson correlation coefficient (r)	0.4697
P-value	<0.0001
Sample size (n)	4
Statistic	42.2470

Figure 10. Analyze Day-to-Day Variation of Observed Volumes

Other Characteristics

The research team collected four turn-lane characteristics (as indicated in Figure 3) for each site. Out of the 33 control sites, 25 have the same turn-lane configuration as their corresponding experimental sites.

Satellite imagery and street views from Google Maps were used to examine sight obstructions. Nineteen sites were found to have fixed-object-related obstructions, while six sites were obstructed by vehicle parking. For example, in Figure 11, the speed limit of the mainline road for both sites is 25 mph, corresponding to an SSD is 155 feet. At site C1 (Figure 11(a)), fixed objects such as trees were present in the sight triangle, so the fixed-object-related obstruction indicator was recorded as 1. Similarly, vehicle parking intruded the sight triangle at site C14 (Figure 11Figure 11(b)), and thus the parking-related obstruction indicator was recorded as 1.

In contrast, at the site E14 with a wide median, as shown in Figure 12, the sight distance triangle on the left was clear, while the triangle on the right contained fixed objects like trees. E14 was identified free of obstruction, because drivers can take refuge in the wide median when making a left turn and their line of sight would not be obstructed by the trees on the right. The characteristics are shown in Table 5.

(a)Example of fixed-object-related obstruction (C1) (b)Example of parking-related obstruction (C14)

Figure 11. Example of Road Clearance Investigations, Map data © 2024 Google

Figure 12. Example of Obstruction for Sites with a Wide Median (E14), Map data © 2024 Google

Table 5. Characteristics of the Control and Experimental Sites

Variables	Descriptions	Control Group		Experimental Group	
		Mean	Standard Deviation	Mean	Standard Deviation
Left Turn at Intersection A	The number of left-turn lanes on the mainline for Intersection A	0.12	0.33	0.12	0.33
Right Turn at Intersection A	The number of right-turn lanes on the mainline for Intersection A	0.09	0.29	0.09	0.29
Left Turn at Intersection B	The number of left-turn lanes on the mainline for Intersection B	0.15	0.36	0.12	0.33
Right Turn at Intersection B	The number of right-turn lanes on the mainline for Intersection B	0.12	0.33	0.15	0.36
Total Turn Lanes	The total number of turn lanes on the mainline	0.48	0.83	0.48	0.80
Mainline Volume	The mean of StreetLight mainline volumes of two intersections (veh/day)	10,275	7,057	10,649	7,560
Access Volumes	The sum of StreetLight access volumes of two intersections (veh/day)	708	615	573	655
Obstruction-Fixed Object	1 for fixed-object-related obstruction, 0 for no obstruction	0.21	0.42	0.36	0.49
Obstruction-Parking	1 for parking-related obstruction, 0 for no obstruction	0.12	0.33	0.06	0.24

Assess Impacts of Access Spacing on Crashes

The two-sided paired t-test and RENB model described in the Methods section were utilized to investigate the impacts of access spacing, with results reported as follows.

Method 1: Two-Sided Paired T-Test

Two-sided paired t-tests were conducted to determine if there are significant differences in crash counts between the control and experimental sites. As shown in Table 6, the p-value for total crashes is 0.1235, suggesting a marginally significant difference in mean total crash counts between the control and experimental sites. In contrast, the p-value for severe crashes is 0.7681, indicating no significant difference in mean severe crash counts between the two groups.

Table 6. Two-Sided Paired T-test

	Test Statistics	P-value
Total Crashes	1.5820	0.1235[a]
Severe Crashes	-0.2973	0.7681

[a] Significance levels: for $0.05 \leq$ p-value < 0.1; * for $0.01 \leq$ p-value < 0.05; ** for $0.001 \leq$ p-value < 0.01; *** for p-value < 0.001.

Method 2: Random Effects Negative Binomial (RENB) Models

Five RENB models were developed for comparison, with their specifications described as follows:

- **Model 1**: Basic model with only the experimental group indicator as the variable.
- **Model 2**: Extends Model 1 by incorporating a covariate of the total number of turn lanes to evaluate its effect.

- **Model 3**: A comprehensive model that includes all relevant covariates, such as total turn lanes, mainline volume, access volume, fixed-object-related obstruction, and parking-related obstruction.
- **Model 4**: Refines Model 3 by excluding the parking-related obstruction covariate, which was found to be insignificant.
- **Model 5**: Uses the logarithm of the product of mainline and access volumes as a combined exposure indicator, enabling comparison with Model 4, which follows the *Highway Safety Manual* (AASHTO, 2010) specification by using the logarithm of mainline volume and access volume separately as exposure indicators.

The results of RENB models for total crashes are reported in Table 7, while results for severe crashes are presented in Table 8. Shorter spacing between access points was associated with a higher number of total crashes, as indicated by the consistently significant coefficients of the experimental group indicator, ranging from 0.37 to 0.43. However, shorter spacing did not have a significant effect on severe crashes. Both mainline and access volumes, as well as the product of these volumes, were found to have a significantly positive impact on total crashes. The presence of fixed-object-related obstructions increased the likelihood of total crashes, whereas parking-related obstructions had no such impact. The total number of turn lanes showed a marginally significant positive effect (p-value =0.0731) on severe crashes in Model 2. This might be attributed to increased conflict points and complexity of maneuvers at intersections with more turn lanes. However, no variable in all the other severe crash models were found to be statistically significant.

Table 7 RENB Models for Total Crashes (Developed on 33 Pairs of Sites)

Variables	Model 1		Model 2		Model 3		Model 4		Model 5	
	Coef.	**P-value**	**Coef.**	**P-value**	**Coef.**	**P-value**	**Coef.**	**P-value**	**Coef.**	**P-value**
Experimental Group	0.3663	0.0748 .[a]	0.3931	0.0621 .	0.3997	0.0195*	0.3946	0.0191*	0.4287	0.0190*
Total Turn Lanes	-	-	0.3721	0.0235*	0.1700	0.2249	0.1642	0.2322	0.1886	0.1687
Log (Mainline Volume)	-	-	-	-	0.3813	0.0071**	0.3817	0.0072**	-	-
Log (Access Volume)	-	-	-	-	0.2096	0.0346*	0.2091	0.0347*	-	-
Log (Product of Volume)	-	-	-	-	-	-	-	-	0.2814	0.0008***
Obstruction-Fixed Object	-	-	-	-	0.5148	0.0165*	0.5297	0.0098**	0.4759	0.0273*
Obstruction-Parking	-	-	-	-	0.0758	0.8544	-	-	-	-
AIC	283.0	-	280.3	-	274.9	-	273.1	-	269.9	-
BIC	291.7	-	291.2	-	294.6	-	290.6	-	285.2	-
Log likelihood	-137.5	-	-135.1	-	-128.4	-	-128.6	-	-128.0	-

[a] Significance levels: for $0.05 \leq$ p-value < 0.1; * for $0.01 \leq$ p-value < 0.05; ** for $0.001 \leq$ p-value < 0.01; *** for p-value < 0.001.

Table 8 RENB Models for Severe Crashes (Developed on 33 Pairs of Sites)

Variables	Model 1		Model 2		Model 3		Model 4		Model 5	
	Coef.	P-value	Coef.	P-value	Coef.	P-value	Coef.	P-value	Coef.	P-value
Experimental Group	-0.2231	0.751[a]	-0.1983	0.7701	-0.4045	0.587	-0.2390	0.740	-0.3123	0.655
Total Turn Lanes	-	-	0.6391	0.0731 .	0.6209	0.166	0.5988	0.113	0.5908	0.121
Log (Mainline Volume)	-	-	-	-	-0.2198	0.596	-0.0792	0.812	-	-
Log (Access Volume)	-	-	-	-	0.0999	0.770	0.1081	0.750	-	-
Log (Product of Volume)	-	-	-	-	-	-	-	-	0.0190	0.933
Obstruction-Fixed Object	-	-	-	-	0.7561	0.293	0.6262	0.371	0.6248	0.371
Obstruction-Parking	-	-	-	-	-32.64	1.000	-	-	-	-
AIC	62.9	-	62.0	-	66.8	-	67.0	-	65.2	-
BIC	71.7	-	73.0	-	86.5	-	84.6	-	80.5	-
Log likelihood	-27.5	-	-26.0	-	-24.4	-	-25.5	-	-25.6	-

[a] Significance levels: for $0.05 \leq$ p-value < 0.1; [*] for $0.01 \leq$ p-value < 0.05; [**] for $0.001 \leq$ p-value < 0.01; [***] for p-value < 0.001.

For total crashes, Model 5 outperformed the others in terms of Akaike Information Criterion (AIC), Bayesian Information Criterion (BIC), and log-likelihood. For severe crashes, Model 2 had the best performance based on AIC and BIC, while Model 3 achieved the highest log-likelihood. Likelihood ratio tests were conducted to further compare the goodness of fit between competing RENB models with different numbers of variables.

As shown in Table 9, the p-values of the likelihood ratio tests for total crashes between Models 2, 3, 4, 5 and Model 1 were less than 0.05, rejecting the null hypothesis at a 95% confidence level and indicating that Models 2, 3, 4, and 5 were significantly different from Model 1 in terms of goodness of fit. Similarly, the p-values for total crashes between Models 3, 4, 5 and Model 2 were less than 0.01, also rejecting the null hypothesis at a 95% confidence level and indicating that Models 3, 4, and 5 were significantly different from Model 2. However, Models 3, 4, and 5 were not significantly different from each other.

Table 9. P-values of Likelihood Ratio Tests of the Whole Model Relative to Other Models for Total Crashes

	Model 1	Model 2	Model 3	Model 4	Model 5
Model 1	-	-	-	-	-
Model 2	0.0285[*a]	-	-	-	-
Model 3	0.0027[**]	0.0095[**]	-	-	-
Model 4	0.0014[**]	0.0046[**]	0.5271	-	-
Model 5	0.0003[***]	0.0008[***]	0.6703	0.2733	-

[a] Significance levels: for $0.05 \leq$ p-value < 0.1; [*] for $0.01 \leq$ p-value < 0.05; [**] for $0.001 \leq$ p-value < 0.01; [***] for p-value < 0.001.

In Table 10, the p-values of the likelihood ratio tests for severe crashes between Model 2 and Model 1 were less than 0.1, rejecting the null hypothesis at a 95% confidence level and indicating that Model 2 was significantly different from Model 1. However, there was no evidence the other models differed significantly from each other in terms of goodness of fit.

Table 10. P-values of Likelihood Ratio Tests of the Whole Model Relative to Other Models for Severe Crashes

	Model 1	Model 2	Model 3	Model 4	Model 5
Model 1	-	-	-	-	-
Model 2	0.0833.	-	-	-	-
Model 3	0.2872	0.5249	-	-	-
Model 4	0.4060	0.8013	0.1380	-	-
Model 5	0.2839	0.6703	0.3012	0.6547	-

[a] Significance levels: for $0.05 \leq$ p-value < 0.1; * for $0.01 \leq$ p-value < 0.05; ** for $0.001 \leq$ p-value < 0.01; *** for p-value < 0.001.

Examine VDOT's Access Management Standards

There were 25 control sites identified with access spacing greater than the minimum required by VDOT's standards, paired with corresponding experimental sites with access spacing below the standard. These 25 pairs of sites were used to evaluate the effectiveness of VDOT's standards. For this analysis, Models 1, 4, and 5 were applied: Model 1 served as the basic mode, Model 4 followed the HSM specification, and Model 5 included a better form of exposure indicators.

The coefficient for the experimental group indicator in Model 5, as shown in Table 11, suggests that violating VDOT's standards is expected to increase total crashes by 64.8% ($e^{0.4995} - 1$). However, when assessing the effectiveness of VDOT's standards for severe crashes, the impact of the experimental group was not as significant, as indicated in Table 12.

Table 11. RENB Models for Total Crashes (Developed on 25 Pairs of Sites)

	Model 1		Model 4		Model 5	
	Coefficient	P-value	Coefficient	P-value	Coefficient	P-value
Experimental Group	0.3664	0.109	0.4953	0.0425*a	0.4995	0.0618 .
Total Turn Lanes	-	-	0.1350	0.4332	0.2111	0.2234
Log (Mainline Volume)	-	-	0.5227	0.0182*	-	-
Log (Access Volume)	-	-	0.2390	0.0362*	-	-
Log (Product of Volume)	-	-	-	-	0.2969	0.0067**
Obstruction-Fixed Object	-	-	0.3629	0.2133	0.2692	0.3818
AIC	235.0	-	203.7	-	202.6	-
BIC	242.9	-	219.0	-	216.0	-
Log likelihood	-113.5	-	-93.9	-	-94.3	-

[a] Significance levels: for $0.05 \leq$ p-value < 0.1; * for $0.01 \leq$ p-value < 0.05; ** for $0.001 \leq$ p-value < 0.01; *** for p-value < 0.001.

Table 12. RENB Models for Severe Crashes (Developed on 25 Pairs of Sites)

	Model 1		Model 4		Model 5	
	Coefficient	**P-value**	**Coefficient**	**P-value**	**Coefficient**	**P-value**
Experimental Group	-0.5108	0.5046[a]	-0.8236	0.351	-0.8492	0.329
Total Turn Lanes	-	-	0.4557	0.300	0.4567	0.305
Log (Mainline Volume)	-	-	0.1307	0.783	-	-
Log (Access Volume)	-	-	0.2192	0.591	-	-
Log (Product of Volume)	-	-	-	-	0.1836	0.562
Obstruction-Fixed Object	-	-	0.6371	0.427	0.6429	0.423
AIC	55.2	-	54.0	-	52.0	-
BIC	63.2	-	69.3	-	65.4	-
Log likelihood	-23.6	-	-19.0	-	-19.0	-

[a] Significance levels: for $0.05 \leq$ p-value < 0.1; * for $0.01 \leq$ p-value < 0.05; ** for $0.001 \leq$ p-value < 0.01; *** for p-value < 0.001.

DISCUSSION

Two methods were employed to investigate the impact of access spacing on total and severe crashes. The two-sided paired t-test indicated a marginally significant difference in mean total crash counts between the control and experimental sites. The RENB Models 4 and 5, which accounted for exposure indicators and other covariates (such as the number of turn lanes and fixed-object-related obstructions), suggested that shorter spacing significantly increased total crashes. Model 5 outperformed Model 4, indicating that using the logarithm of the product of access and mainline volume is a more effective approach for accommodating the exposure indicator in this analysis. According to the coefficient of the experimental group indicator in Model 5 (presented in Table 7), shorter access spacing was associated with a 53.5% ($e^{0.4287} - 1$) increase in total crashes. In contrast, both the two-sided paired t-test and all five RENB models consistently suggested that access spacing did not have a significant effect on severe crashes. This finding aligns with the results from Phase I, where shorter spacing was found to result in more rear-end crashes, which are typically not severe.

To evaluate VDOT's Access Management Standard, 25 pairs of sites out of the 33 were utilized, where the control sites had access spacing greater than the minimum standard, while the corresponding experimental sites had access spacing below the standard. The coefficient for the experimental group indicator in Model 5 (as shown in Table 11) suggested that violating VDOT's standards was expected to increase total crashes by 64.8% ($e^{0.4995} - 1$), which is a larger effect than the 53.5% increase observed across all 33 pairs of sites. This difference is reasonable, as the 25 pairs used in this analysis have an even greater discrepancy in access spacing. On the other hand, data from the 25 pairs of sites indicated that violating VDOT's standards did not significantly affect severe crashes. This study highlighted the importance of maintaining VDOT's current standards on minimum access spacing.

CONCLUSIONS

- *Shorter spacing between access points leads to a higher number of total crashes* ($p<0.02$ for Models 3-5, as shown in Table 7).

- *Violating the VDOT's standards on minimum access spacing is expected to increase the total crashes by 64.8%* (based on Model 5 shown in Table 11).

- *Shorter spacing does not have a significant impact on severe crashes* ($p = 0.59$ to 0.74 based on Models 3-5 shown in Table 8).

- *The presence of fixed-object-related sight distance obstruction increases the likelihood of total crashes* ($p<0.03$ for Models 3-5, as shown in Table 7).

- *The total number of turn lanes has a marginally significant positive effect on severe crashes* ($p=0.07$ based on Model 2 in Table 8).

RECOMMENDATION

1. *The Office of Land Use should continue to maintain the existing minimum spacing standards for accesses presented in Table 2-2 of Appendix F of the VDOT Road Design Manual.*

IMPLEMENTATION AND BENEFITS

Researchers and the technical review panel for the project (listed in the Acknowledgments) collaborated to craft a plan to implement the study recommendations and determine the benefits of doing so. This will ensure the implementation plan is developed and approved with the participation and support of those involved with VDOT operations. The implementation plan and the accompanying benefits are provided here.

Implementation

To implement the recommendation, there are two action items.

- The Office of Land Use will continue to uphold the existing minimum spacing standards for access points as specified in Table 2-2 of Appendix F of the *VDOT Road Design Manual*. This involves rigorously applying these standards when reviewing access exception requests and ensuring that any deviations are strictly limited and supported by thorough justification.

- Within one year of this report's publication, the Office of Land Use will update *Instructional and Informational Memoranda LU 501, Access Management Spacing Exceptions/Waivers* (VDOT 2020), to reflect a key finding of this report which is that the data herein suggest that violating VDOT's minimum access spacing standards is expected to increase total crashes by 64.8%.

Benefits

Based on the previous analysis, violating VDOT's minimum access spacing standards is expected to increase total crashes by 64.8%. To be conservative, the unit cost for a property damage only (PDO) crash, estimated by VDOT at $13,743 (VDOT, 2022), is used in this calculation. The average crash frequency at the selected control sites is 0.26 per year. According to the Office of Land Use, there were a total of 92 access exception requests from 2019 to 2023. If we only consider the impact of these 92 requests, it is estimated that approving these exceptions would result in an additional crash cost of $213,018 per year ($13,743 × 0.26 × 92 × 64.8%).

If the access exception requests over a longer period are considered, the annual crash cost could be even higher. Increased crashes may occur each year; thus, approving each exception request would have a cumulative impact on crash costs, leading to a compounding effect over time. This highlights the importance of adhering to VDOT's minimum access spacing standards to prevent escalating crash costs in the long term.

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APPENDIX A. SATELLITE IMAGES OF SELECTED SITES

Figure A1. Control site 1 and Experimental site 1, Map data © 2024 Google

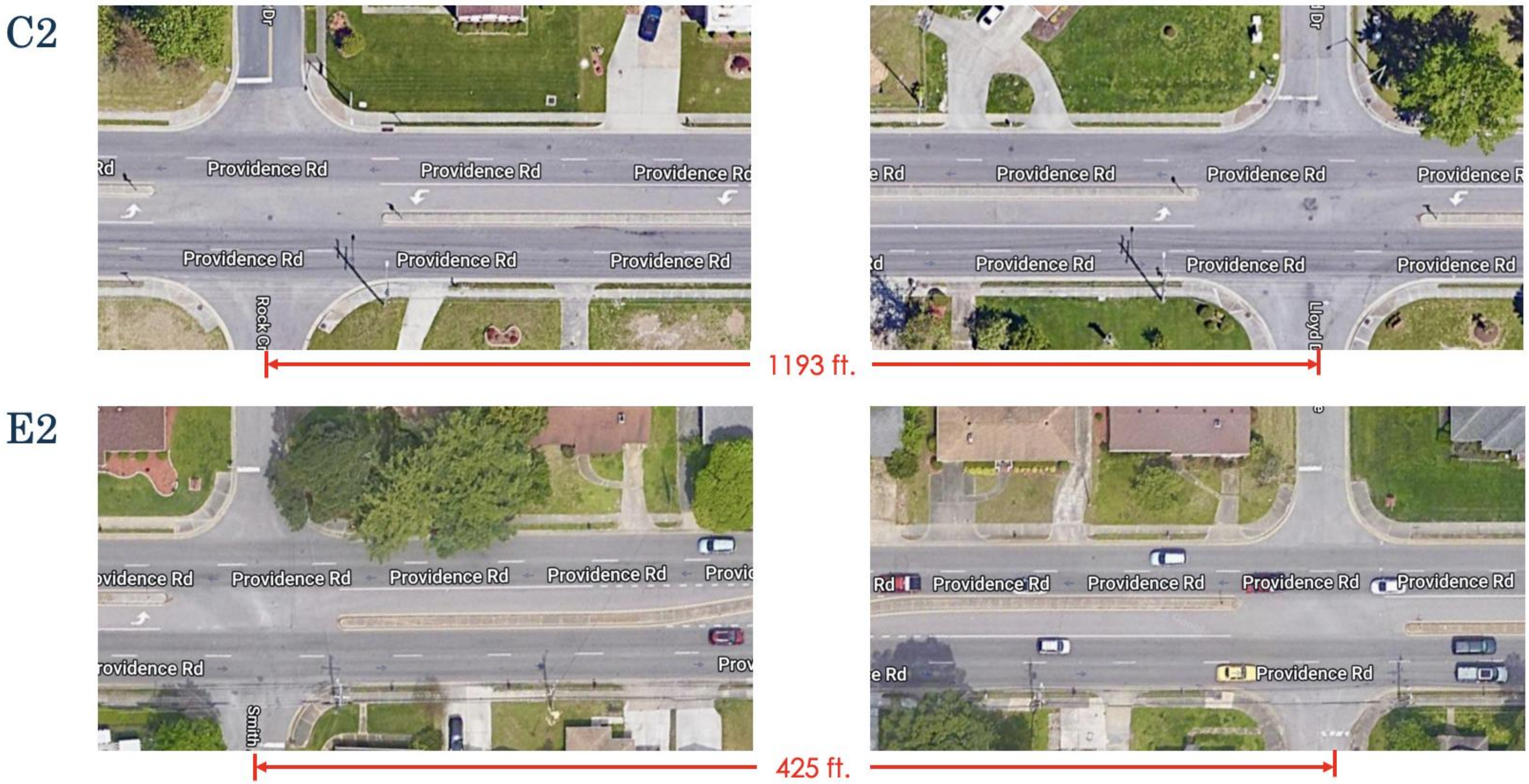


Figure A2. Control site 2 and Experimental site 2, Map data © 2024 Google

Figure A3. Control site 3 and Experimental site 3, Map data © 2024 Google

C4

E4

Figure A4. Control site 4 and Experimental site 4, Map data © 2024 Google

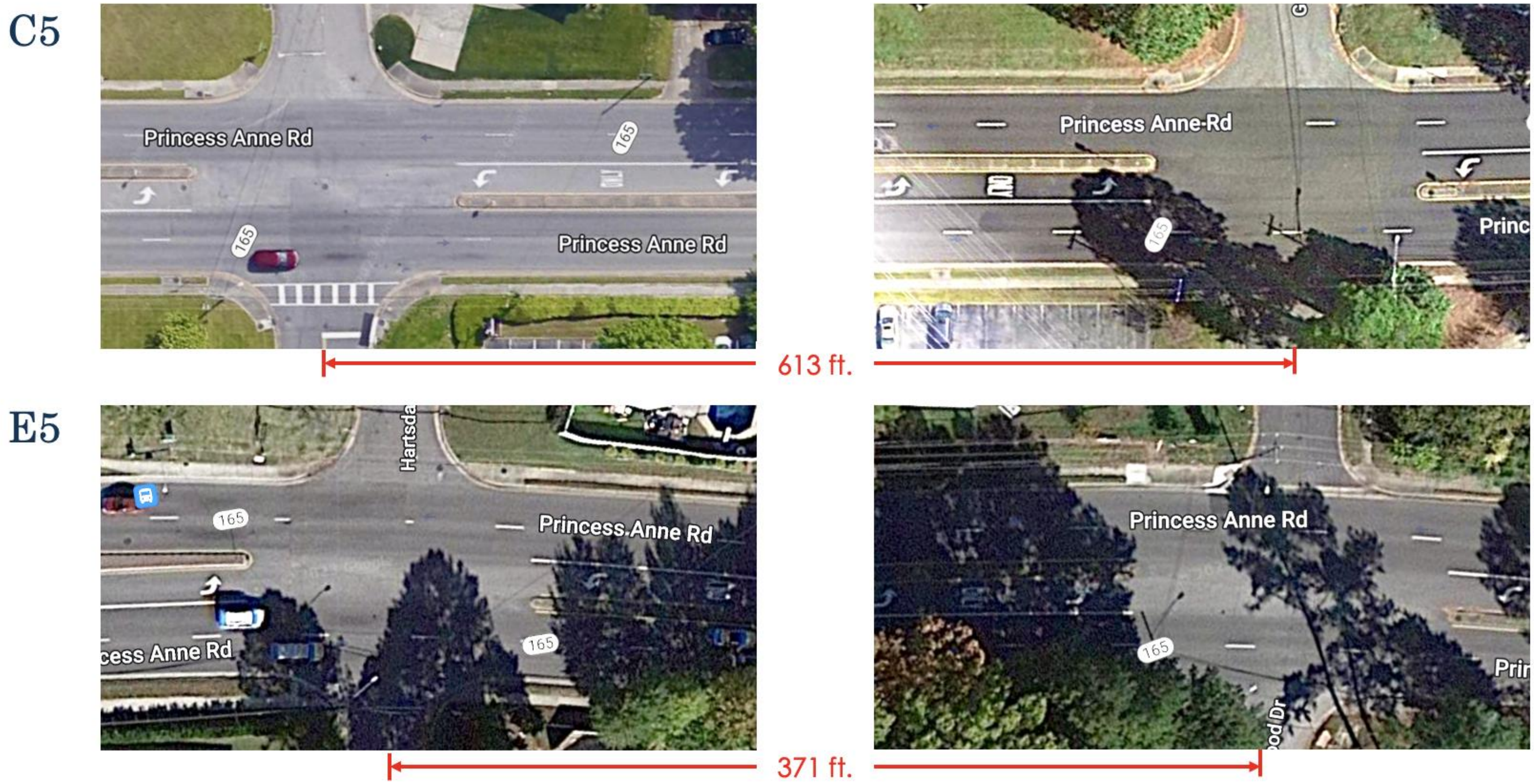


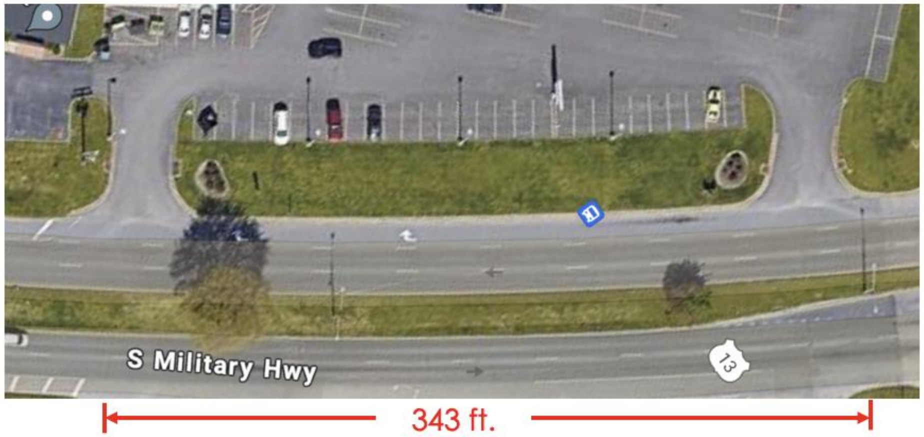
Figure A5. Control site 5 and Experimental site 5, Map data © 2024 Google

C6

E6

Figure A6. Control site 6 and Experimental site 6, Map data © 2024 Google

C7



E7

Figure A7. Control site 7 and Experimental site 7, Map data © 2024 Google

C8

E8

Figure A8. Control site 8 and Experimental site 8, Map data © 2024 Google

Figure A9. Control site 9 and Experimental site 9, Map data © 2024 Google

Figure A10. Control site 10 and Experimental site 10, Map data © 2024 Google

Figure A11. Control site 11 and Experimental site 11, Map data © 2024 Google

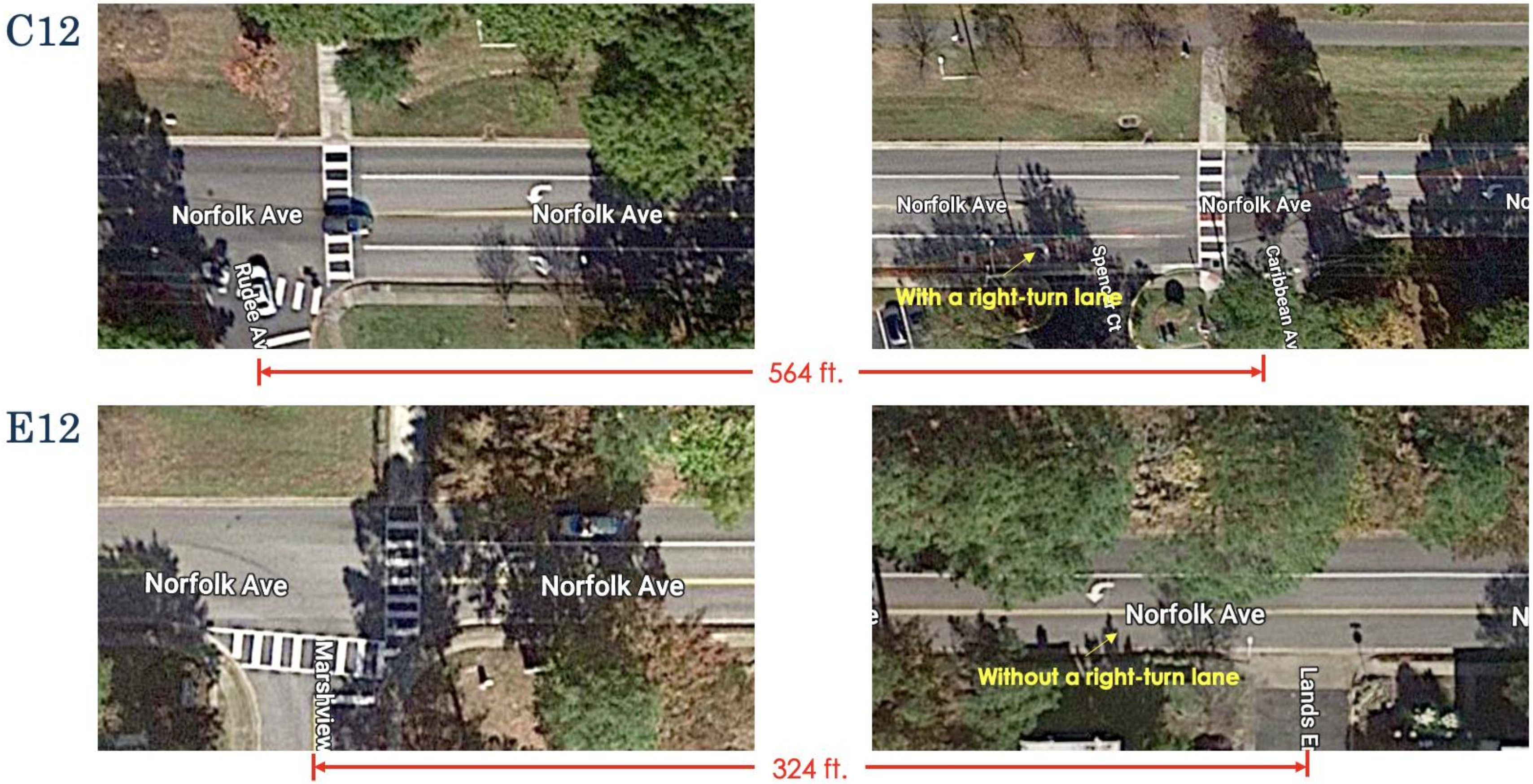


Figure A12. Control site 12 and Experimental site 12, Map data © 2024 Google

Figure A13. Control site 13 and Experimental site 13, Map data © 2024 Google

Figure A14. Control site 14 and Experimental site 14, Map data © 2024 Google

Figure A15. Control site 15 and Experimental site 15, Map data © 2024 Google

C16

E16

Figure A16. Control site 16 and Experimental site 16, Map data © 2024 Google

C17

E17

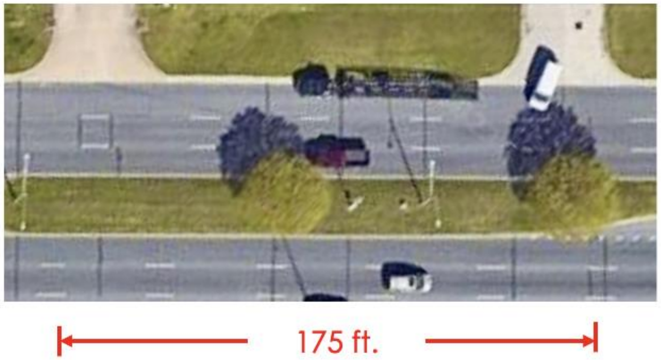


Figure A17. Control site 17 and Experimental site 17, Map data © 2024 Google

Figure A18. Control site 18 and Experimental site 18, Map data © 2024 Google

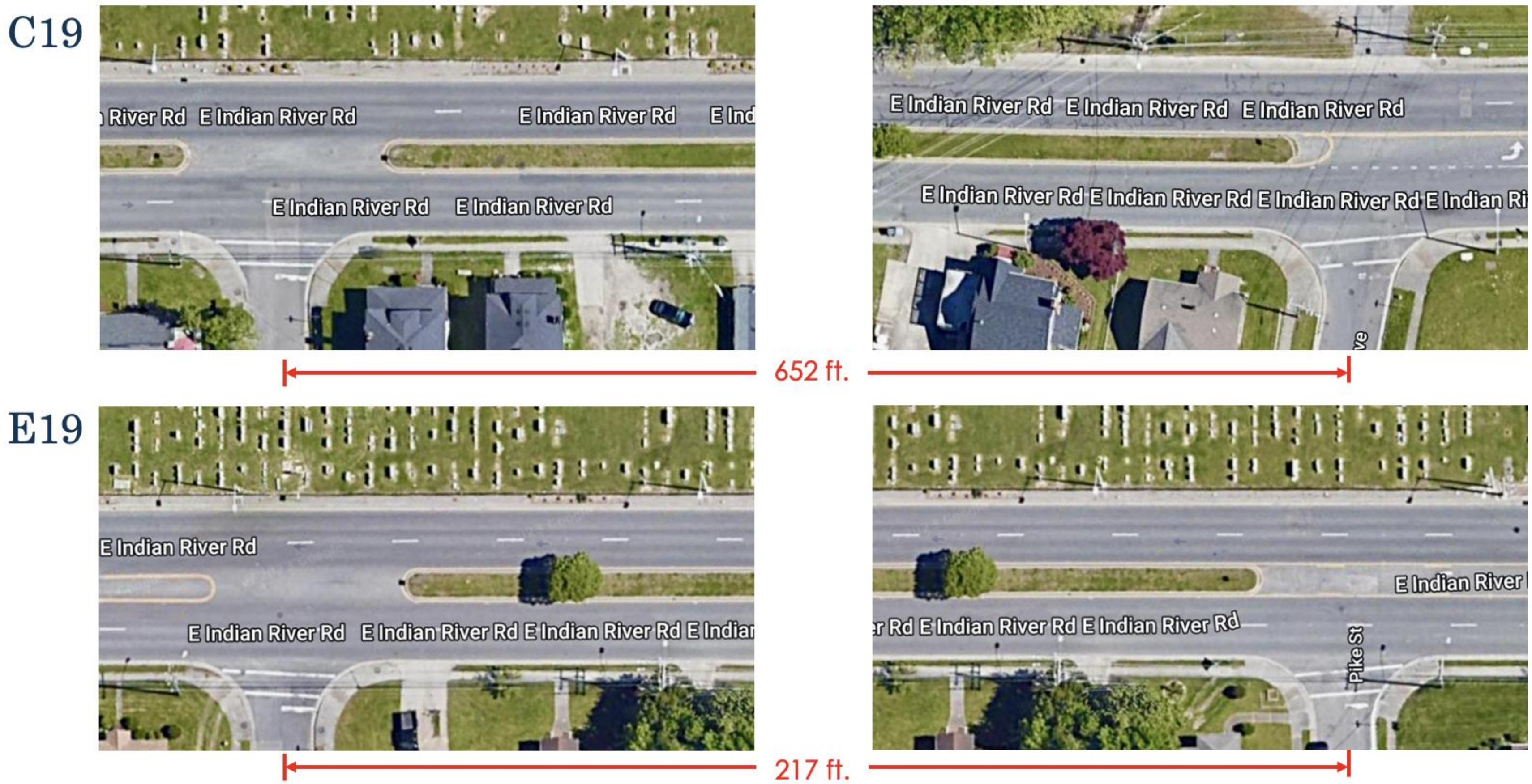


Figure A19. Control site 19 and Experimental site 19, Map data © 2024 Google

Figure A20. Control site 20 and Experimental site 20, Map data © 2024 Google

C21

E21

Figure A21. Control site 21 and Experimental site 21, Map data © 2024 Google

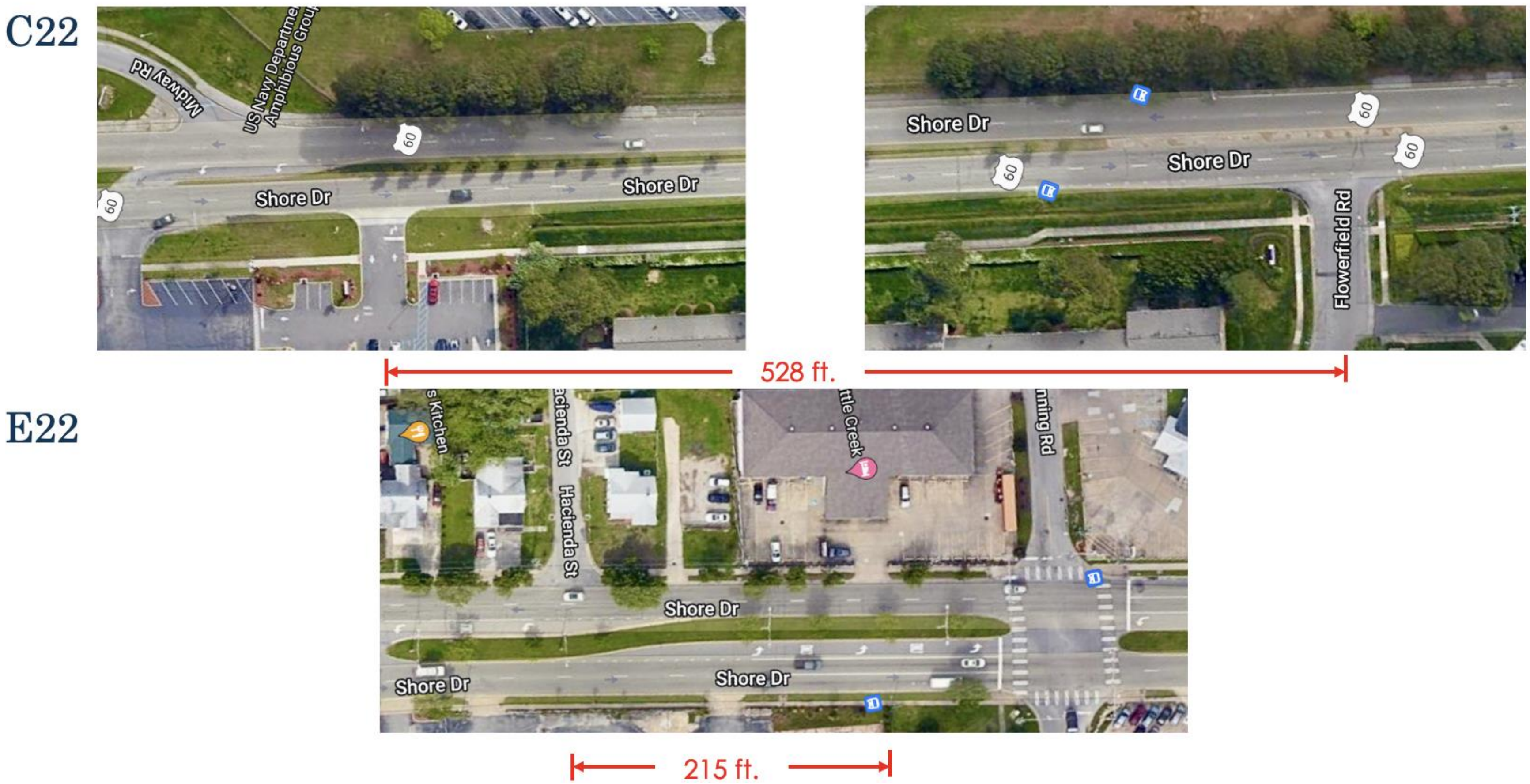


Figure A22. Control site 22 and Experimental site 22, Map data © 2024 Google

C23

E23

Figure A23. Control site 23 and Experimental site 23, Map data © 2024 Google

C24

E24

Figure A24. Control site 24 and Experimental site 24, Map data © 2024 Google

C25

E25

Figure A25. Control site 25 and Experimental site 25, Map data © 2024 Google

C26

E26

Figure A26. Control site 26 and Experimental site 26, Map data © 2024 Google

C27

E27

Figure A27. Control site 27 and Experimental site 27, Map data © 2024 Google

C28

E28

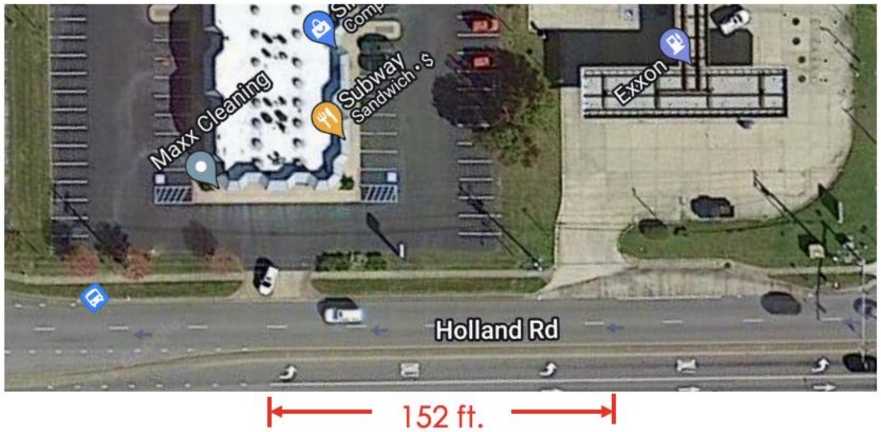


Figure A28. Control site 28 and Experimental site 28, Map data © 2024 Google

C29

E29

Figure A29. Control site 29 and Experimental site 29, Map data © 2024 Google

C30

E30

Figure A30. Control site 30 and Experimental site 30, Map data © 2024 Google

C31

E31

Figure A31. Control site 31 and Experimental site 31, Map data © 2024 Google

C32

E32

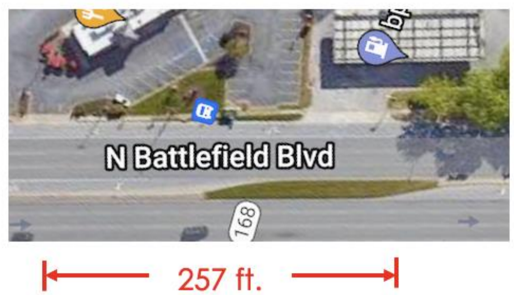


Figure A32. Control site 32 and Experimental site 32, Map data © 2024 Google

C33

E33

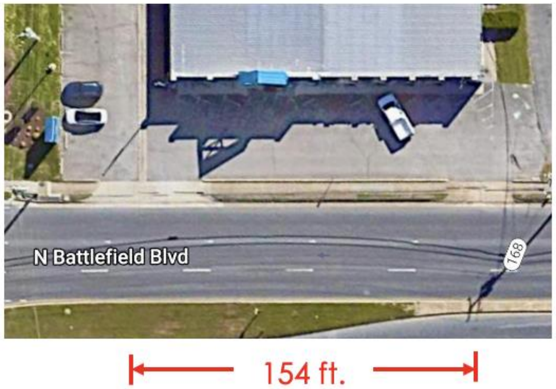


Figure A33. Control site 33 and Experimental site 33, Map data © 2024 Google

APPENDIX B. COMPARISONS OF STREETLIGHT VOLUMES AND OBSERVED VOLUMES

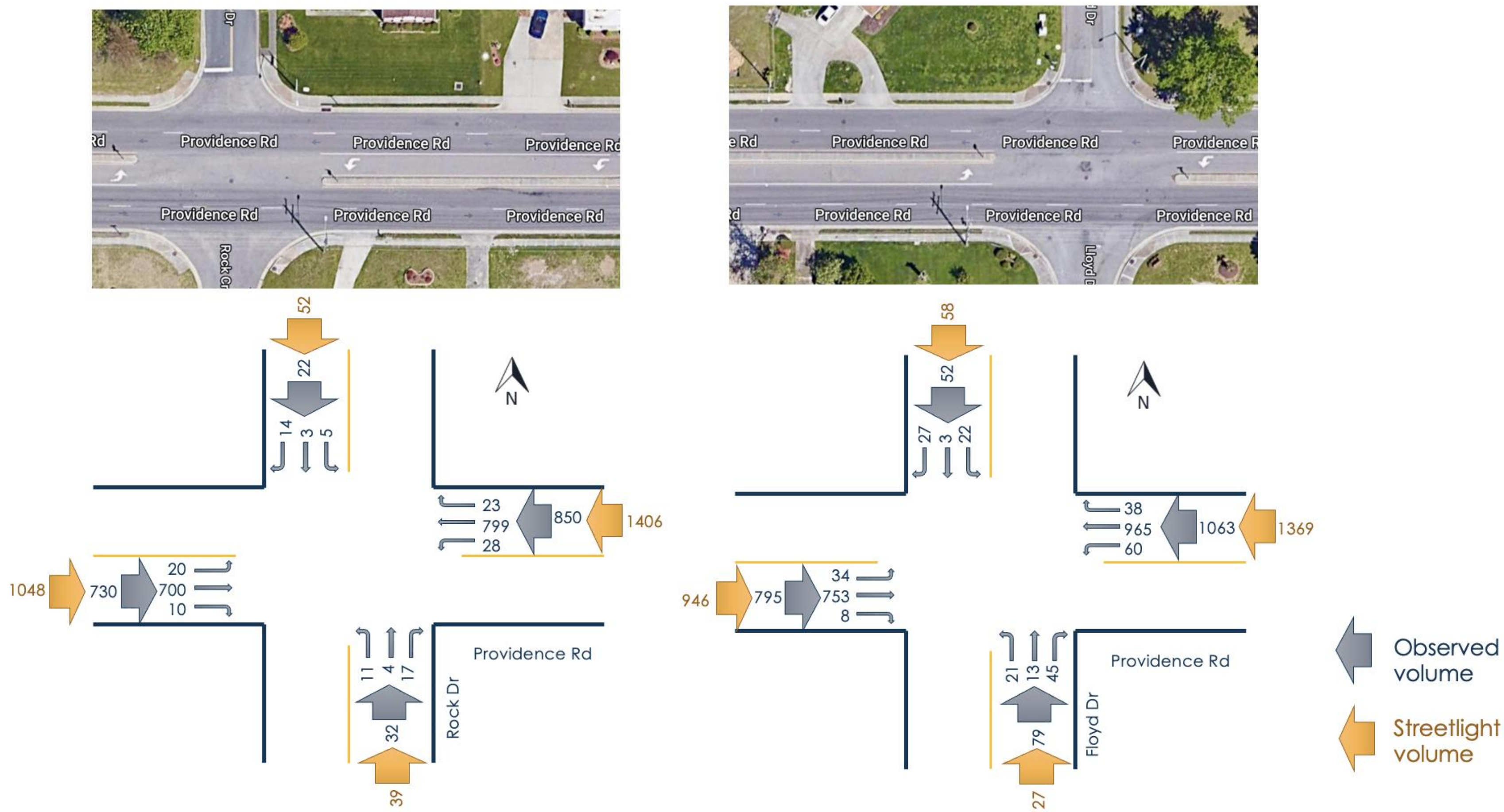


Figure B1. StreetLight Volumes and Observed Volumes for C2 in PM Peak, Map data © 2024 Google

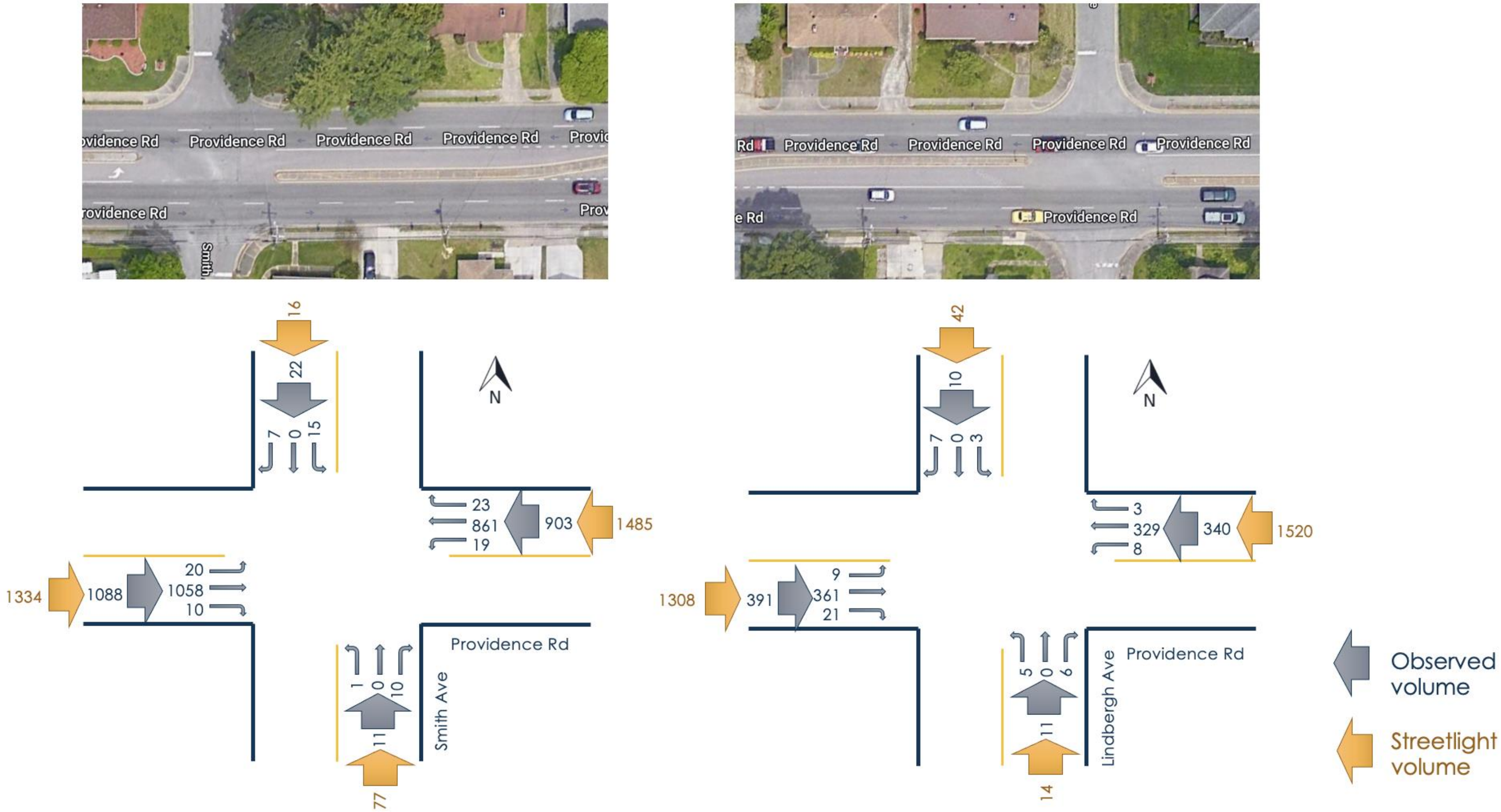


Figure B2. StreetLight Volumes and Observed Volumes for E2 in PM Peak, Map data © 2024 Google

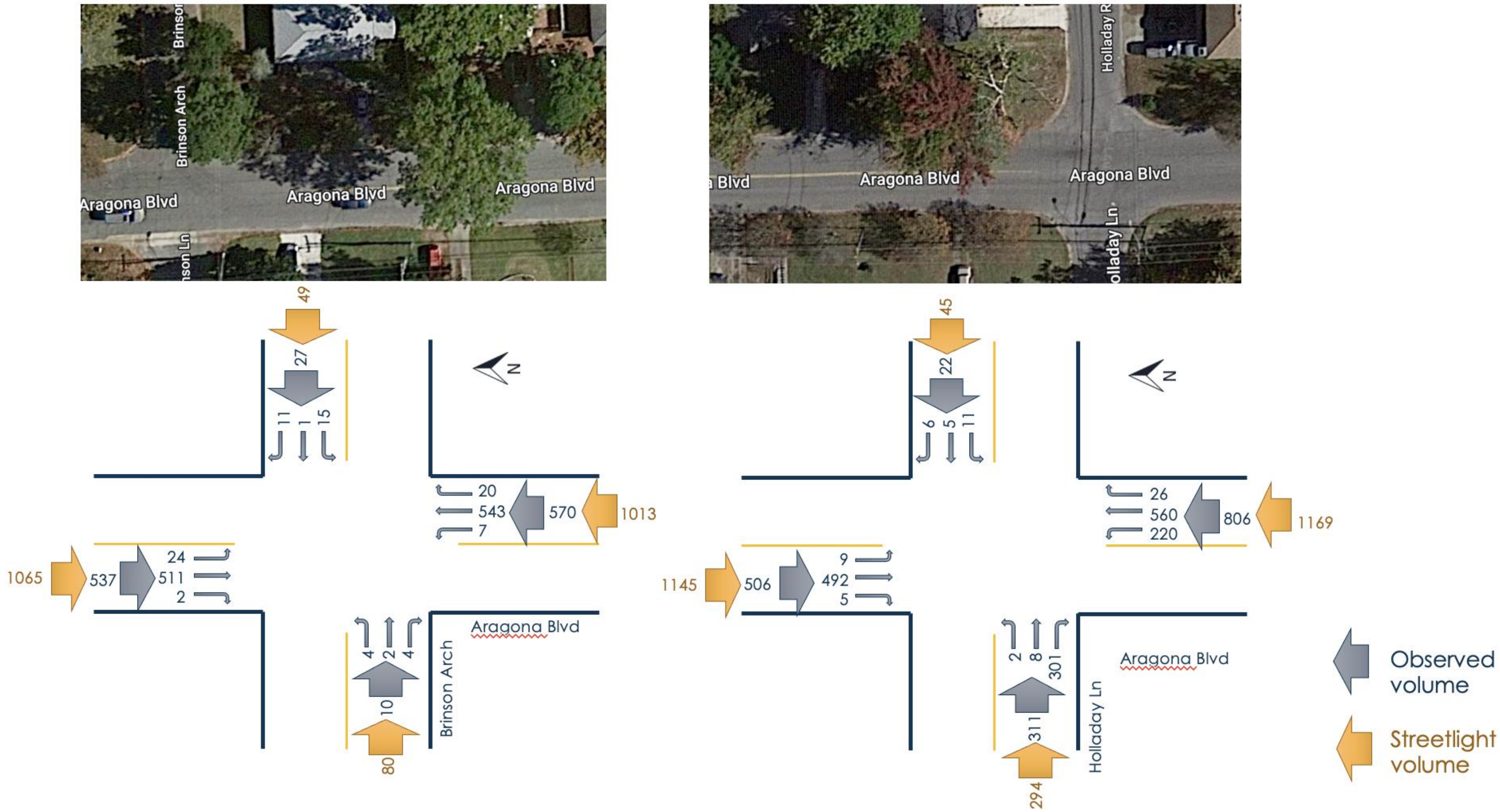


Figure B3. StreetLight Volumes and Observed Volumes for C6 in PM Peak, Map data © 2024 Google

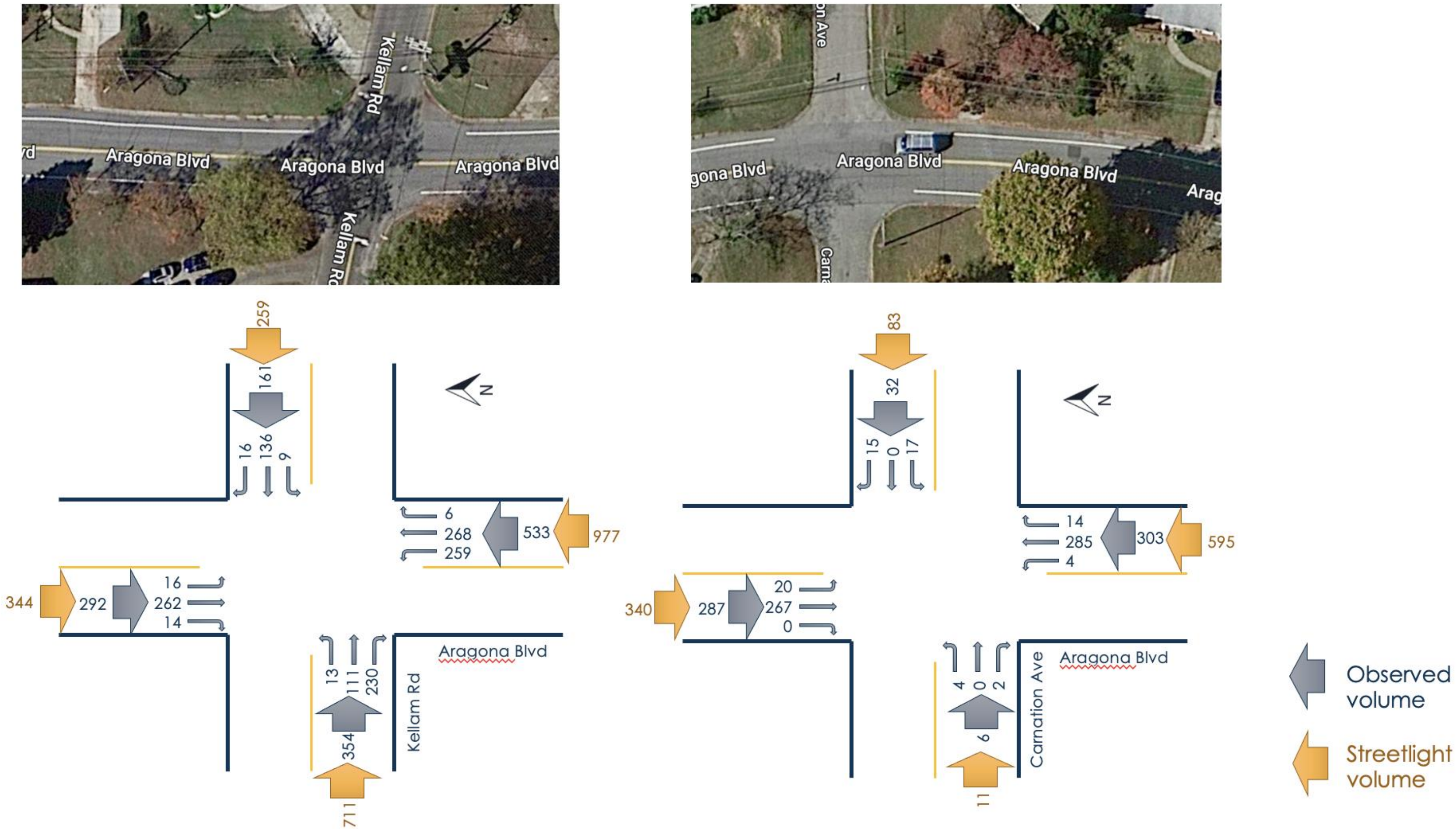


Figure B4. StreetLight Volumes and Observed Volumes for E6 in PM Peak, Map data © 2024 Google

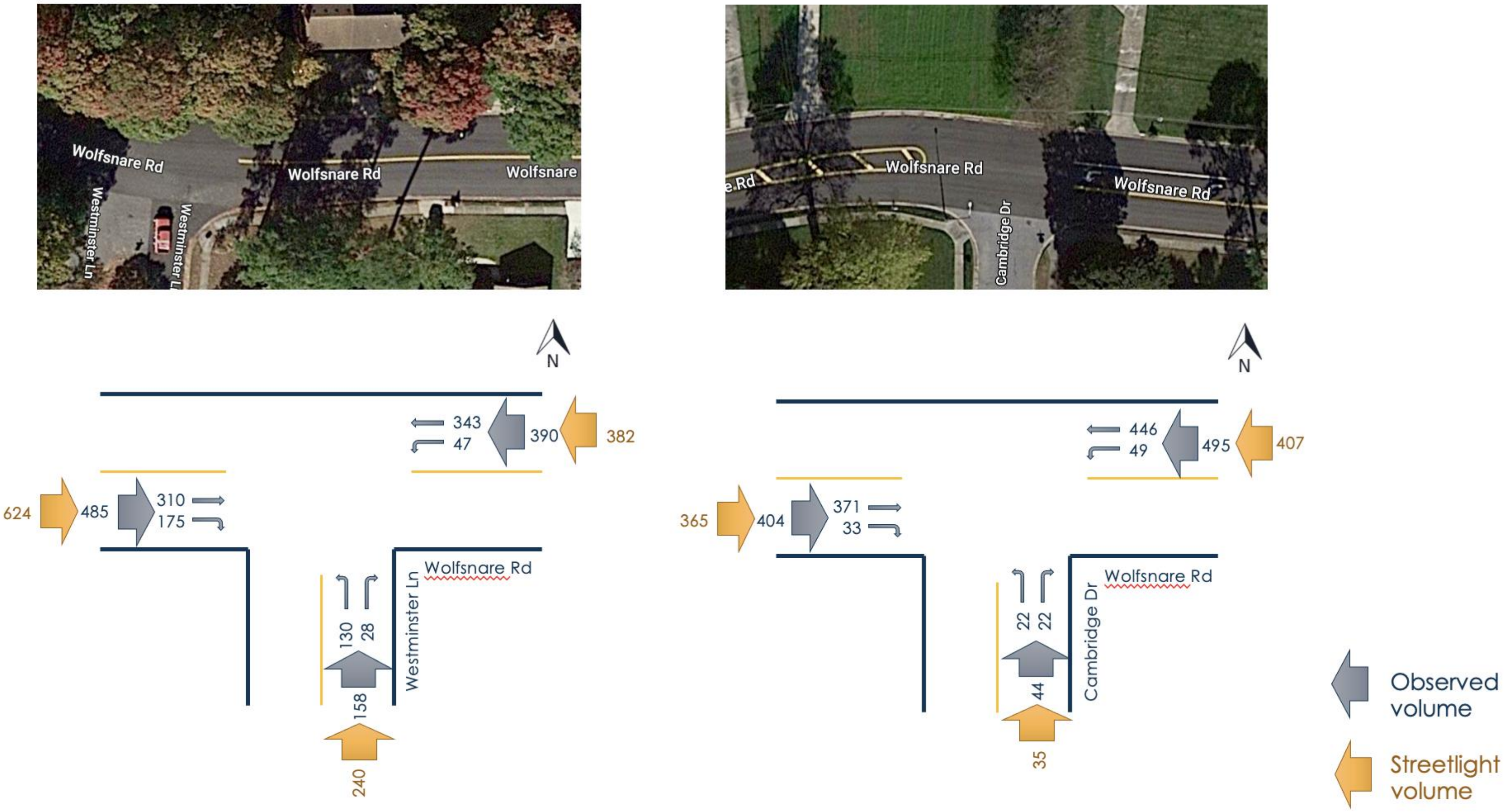


Figure B5. StreetLight Volumes and Observed Volumes for C11 in PM Peak, Map data © 2024 Google

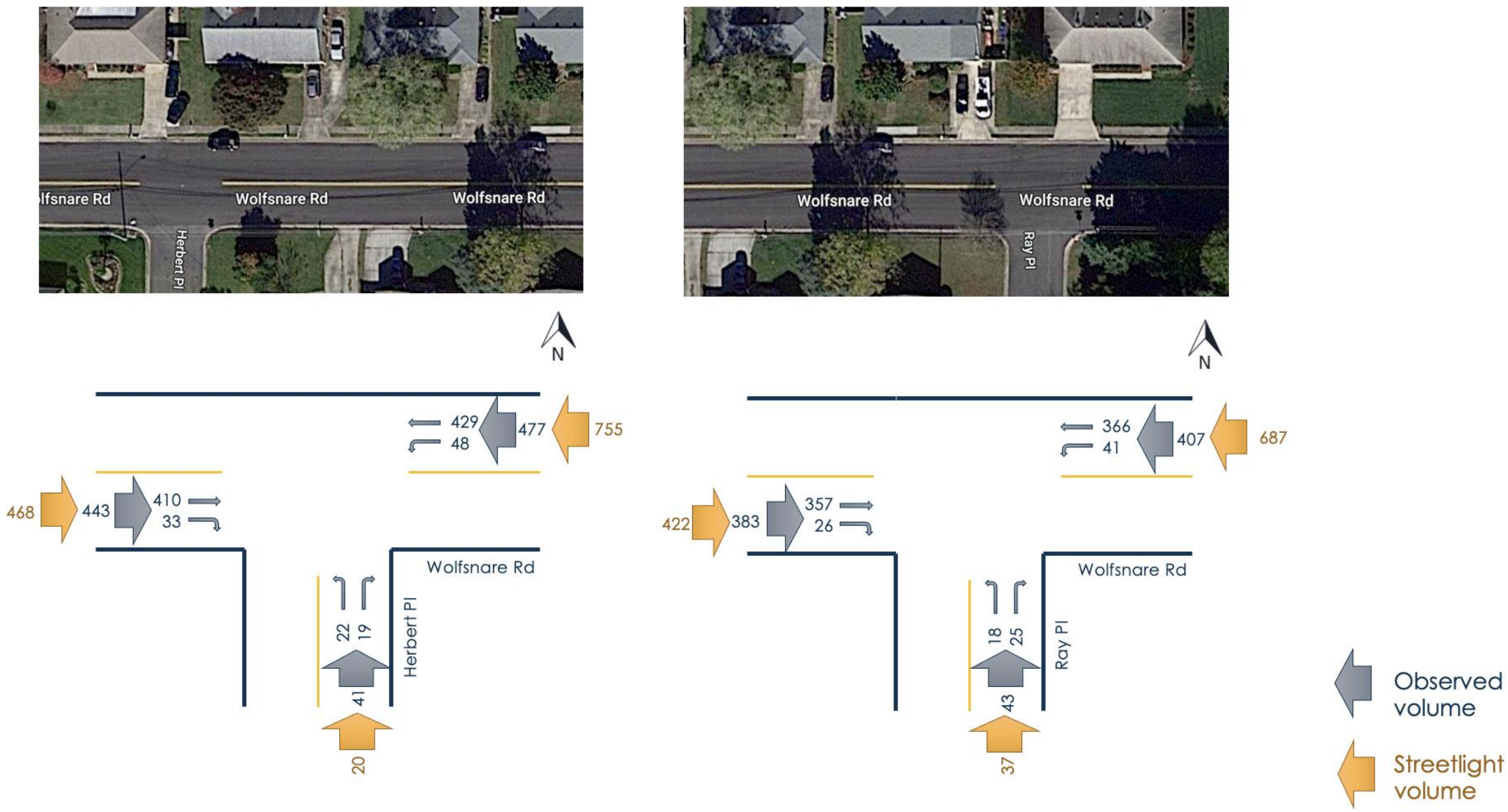


Figure B6. StreetLight Volumes and Observed Volumes for E11 in PM Peak, Map data © 2024 Google

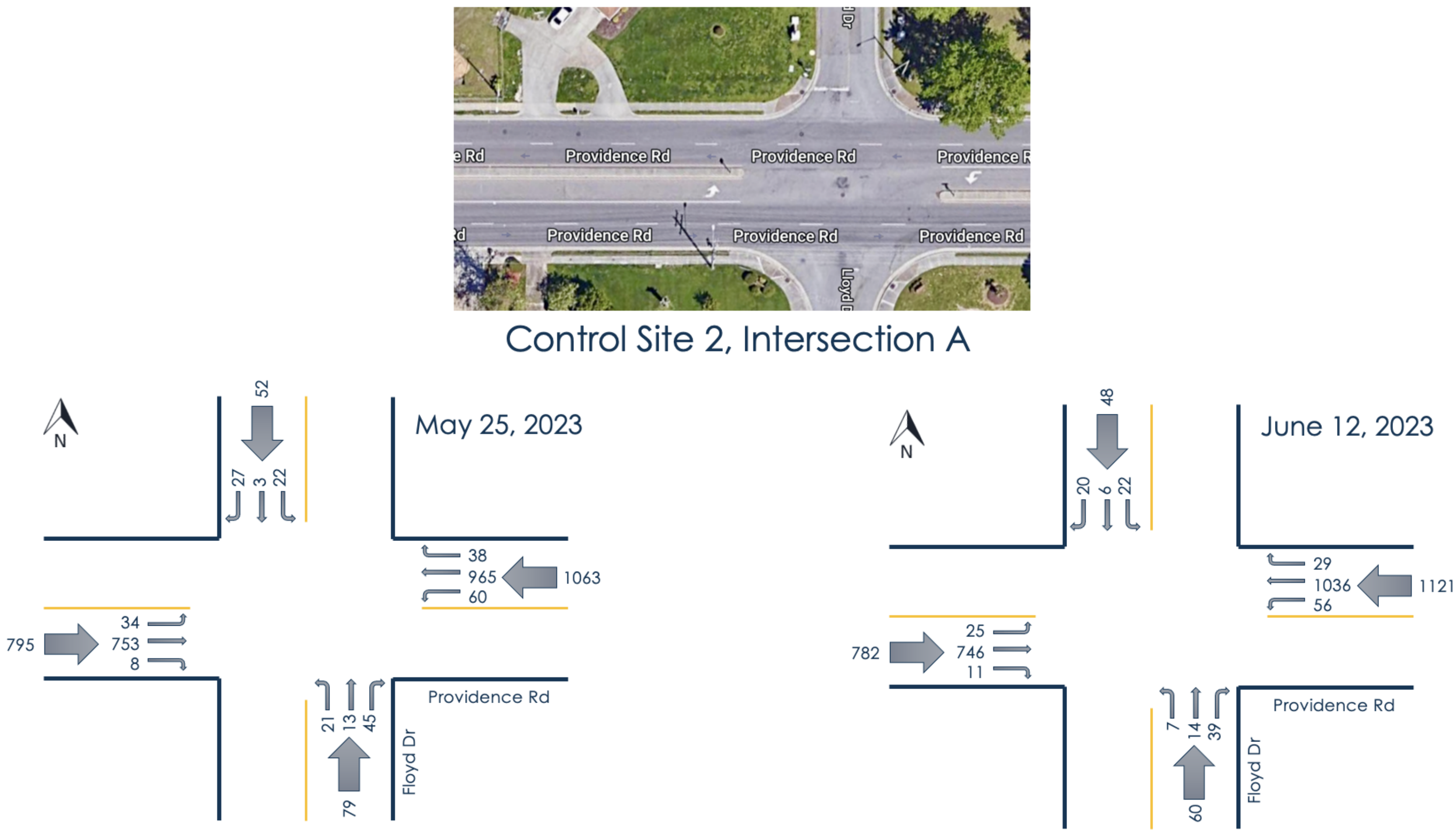


Figure B7. Day-to-Day Variation of Observed Volumes for C2, Intersection A, Map data © 2024 Google

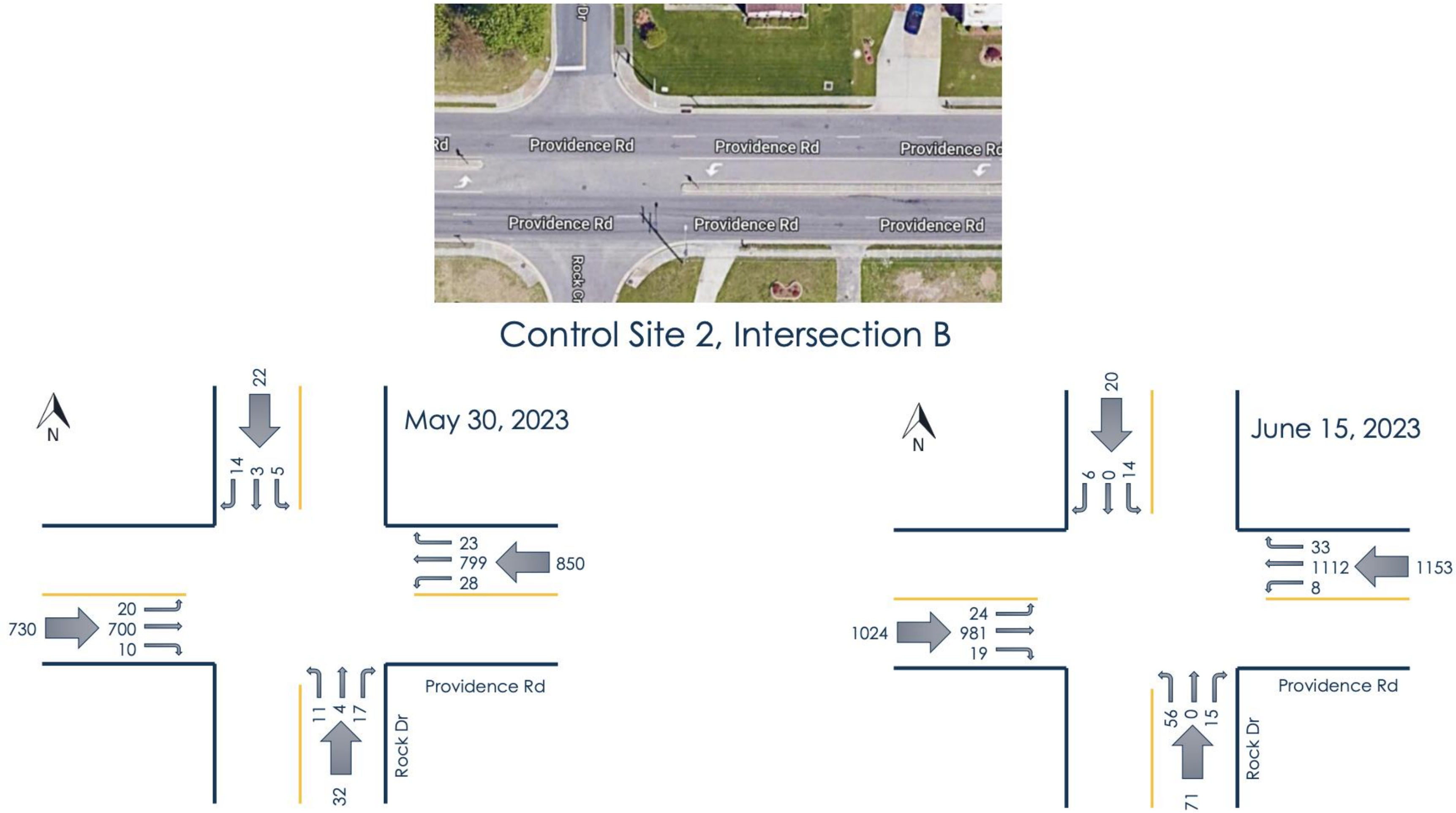


Figure B8. Day-to-Day Variation of Observed Volumes for C2, Intersection B, Map data © 2024 Google