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Virginia Transportation Research Council

research report

Best Practices in Traffic Operations and Safety: Phase II: Zig-zag Pavement Markings

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The Washington and Old Dominion (W&OD) Trail is a 45-mile multiuse trail that spans the Virginia counties of Fairfax and Loudoun. The more than 70 highway crossings of the trail create a significant potential for serious crashes between vehicles and bicyclists/pedestrians. In an attempt to increase safety at two of the crossings, VDOT installed zig-zag pavement markings in Loudoun County where the trail crosses Belmont Ridge Road and Sterling Boulevard.

This study assessed the effectiveness of the zig-zag pavement markings. Effectiveness was defined as: (1) an increase in motorist awareness in advance of the crossing locations; (2) a positive change in motorist attitudes; and (3) motorist understanding of the markings. Motorist awareness was assessed by before and after speed studies. Motorist attitudinal changes were assessed through a survey targeting motorists, pedestrians, and bicyclists familiar with the markings. The survey was distributed via links posted on the Loudoun County government office website and electronic newsletters distributed by the Broad Run and Sterling District supervisors' offices (respective districts for Belmont Ridge Road and Sterling Boulevard). Links were also distributed to bicycle clubs operating throughout the Northern Virginia area. Motorist understanding was assessed through a hand-out survey in a different region of the state that targeted motorists unfamiliar with the zig-zag marking installation in Loudoun County.

The study found that the markings installed in advance of the two crossings heightened the awareness of approaching motorists. This was evidenced by reduced mean vehicle speeds within the marking zones. Further, the majority of survey respondents indicated an increase in awareness, a change in driving behavior, and a higher tendency to yield than before, and the markings had a sustained positive effect on speed reduction. The study also found that motorists have limited understanding regarding the purpose of the markings, and users of the W&OD Trail and motorists are confused regarding who has the right of way at the crossings.

The study recommends that (1) VDOT's Northern Region Traffic Engineering Division lead an effort to recommend to the Federal Highway Administration that zig-zag pavement markings be included in the Manual on Uniform Traffic Control Devices; (2) the National Committee on Uniform Traffic Control Devices adopt as guidance the zig-zag pavement marking design parameters presented in this study; (3) VDOT continue to re-mark and maintain the zig-zag pavement markings at both test locations; (4) VDOT monitor and collect data on crashes at both locations for a 3-year period; and (5) a review of the Code of Virginia be undertaken with respect to those sections of the Code having to do with trail users on multiuse pathways and their obligation to comply with non-signalized traffic control devices.

When the costs of installing zig-zag pavement markings are compared to those of other safety countermeasures and the same effectiveness with respect to crash avoidance is assumed, the benefits of the zig-zag pavement markings far exceed those of a "do nothing" approach and those of the other countermeasures. For example, if two evident injury crashes were avoided over a 5-year period, the monetary benefits associated with the installation of zig-zag pavement markings would be approximately $91,000 compared to approximately $58,000 for advance flashing beacons; overhead flashing beacons would have a monetary disbenefit (cost) of approximately $7,000.</td></tr>
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FINAL REPORT

BEST PRACTICES IN TRAFFIC OPERATIONS AND SAFETY: PHASE II: ZIG-ZAG PAVEMENT MARKINGS

Lance E. Dougald
Research Scientist

In Cooperation with the U.S. Department of Transportation
Federal Highway Administration

Virginia Transportation Research Council
(A partnership of the Virginia Department of Transportation
and the University of Virginia since 1948)

Charlottesville, Virginia

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DEDICATION

This report is dedicated to the memory of Eugene (Gene) Arnold. In his career as a transportation planner and research scientist, he wrote 45 published research reports, contributed to multiple journals and newsletters, and made presentations at numerous state and national professional meetings. Gene retired from VDOT and the Virginia Transportation Research Council on July 1, 2008, after 40 years of service. This project, *Best Practices in Transportation Operations and Safety: Phase II: Zig-Zag Pavement Markings,* was the last project he worked on.

His guidance, tutorship, and friendship will never be forgotten.
May your love forever touch and comfort your family.

ABSTRACT

The Washington and Old Dominion (W&OD) Trail is a 45-mile multiuse trail that spans the Virginia counties of Fairfax and Loudoun. The more than 70 highway crossings of the trail create a significant potential for serious crashes between vehicles and bicyclists/pedestrians. In an attempt to increase safety at two of the crossings, VDOT installed zig-zag pavement markings in Loudoun County where the trail crosses Belmont Ridge Road and Sterling Boulevard.

This study assessed the effectiveness of the zig-zag pavement markings. *Effectiveness* was defined as: (1) an increase in motorist awareness in advance of the crossing locations; (2) a positive change in motorist attitudes; and (3) motorist understanding of the markings. Motorist awareness was assessed by before and after speed studies. Motorist attitudinal changes were assessed through a survey targeting motorists, pedestrians, and bicyclists familiar with the markings. The survey was distributed via links posted on the Loudoun County government office website and electronic newsletters distributed by the Broad Run and Sterling District supervisors' offices (respective districts for Belmont Ridge Road and Sterling Boulevard). Links were also distributed to bicycle clubs operating throughout the Northern Virginia area. Motorist understanding was assessed through a hand-out survey in a different region of the state that targeted motorists unfamiliar with the zig-zag marking installation in Loudoun County.

The study found that the markings installed in advance of the two crossings heightened the awareness of approaching motorists. This was evidenced by reduced mean vehicle speeds within the marking zones. Further, the majority of survey respondents indicated an increase in awareness, a change in driving behavior, and a higher tendency to yield than before, and the markings had a sustained positive effect on speed reduction. The study also found that motorists have limited understanding regarding the purpose of the markings, and users of the W&OD Trail and motorists are confused regarding who has the right of way at the crossings.

The study recommends that (1) VDOT's Northern Region Traffic Engineering Division lead an effort to recommend to the Federal Highway Administration that zig-zag pavement markings be included in the *Manual on Uniform Traffic Control Devices;* (2) the National Committee on Uniform Traffic Control Devices adopt as guidance the zig-zag pavement marking design parameters presented in this study; (3) VDOT continue to re-mark and maintain the zig-zag pavement markings at both test locations; (4) VDOT monitor and collect data on crashes at both locations for a 3-year period; and (5) a review of the *Code of Virginia* be undertaken with respect to those sections of the *Code* having to do with trail users on multiuse pathways and their obligation to comply with non-signalized traffic control devices.

When the costs of installing zig-zag pavement markings are compared to those of other safety countermeasures and the same effectiveness with respect to crash avoidance is assumed, the benefits of the zig-zag pavement markings far exceed those of a "do nothing" approach and those of the other countermeasures. For example, if two evident injury crashes were avoided over a 5-year period, the monetary benefits associated with the installation of zig-zag pavement markings would be approximately $91,000 compared to approximately $58,000 for advance flashing beacons; overhead flashing beacons would have a monetary disbenefit (cost) of approximately $7,000.

FINAL REPORT

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INTRODUCTION

Improving safety on our nation's roadways continues to receive the attention of federal, state, and local officials as well as public and private organizations. Although a study by the National Highway Safety Traffic Administration estimated that approximately 330,000 lives were saved from 1960 to 2005 because of vehicle and roadway safety technologies,[1] a significant number of highway deaths still occurs. Consequently, in 2005, the American Association of State Highway and Transportation Officials announced a state highway safety campaign to reduce fatalities by 9,000 per year nationally.[2,3] These efforts to improve safety are directed toward all modes and users of the transportation system, including pedestrians and bicyclists. Thus, planners and engineers have a responsibility to plan, design, and install safe facilities for these users of the transportation system.[4]

In 1994, the U.S. Department of Transportation adopted a policy of doubling the percentage of trips made by bicycling and walking while simultaneously reducing by 10 percent the number of bicyclists and pedestrians injured in traffic crashes.[5] Further evidence of increased national attention to pedestrian and bicycle safety is the increased Federal-Aid Highway Program funding for pedestrian and bicycle programs and projects from $22.9 million in 1992 to $1.19 billion in 2009.[6] Although these funds are allocated for a variety of different projects and programs—from the construction of trails and sidewalks for better connectivity to enhanced street lighting and crossing treatments—the impetus for this expansion of funding was to create a safer transportation environment for all modes of travel.

Individual states, including Virginia, have incorporated strategic highway safety plans as part of this national emphasis on improving highway safety. The Virginia Department of Transportation's (VDOT) *Policy for Integrating Bicycle and Pedestrian Accommodations*[7] states that VDOT will accommodate bicyclists and pedestrians, including pedestrians with disabilities, along with motorized transportation modes in the planning, funding, design, construction, operation, and maintenance of Virginia's transportation network to achieve a safe, effective, and balanced multimodal transportation system.

Although the United States is considered a leader in technology and best practices regarding traffic operations and safety,[8] there are technologies and practices worldwide that Virginia currently does not employ, some of which may be transferable and supportive of its goal to better integrate bicycle and pedestrian accommodations. Subsequent to the publication of the Federal Highway Administration (FHWA) report entitled *Innovative Traffic Control Technology* *and Practice in Europe*,[9] researchers at the Virginia Transportation Research Council (VTRC) identified 42 technologies and practices used overseas that are not employed in Virginia and evaluated their potential as pilot studies. As a result of the evaluation, 12 measures were categorized as good candidates for piloting, including[8]:

1. colored and textured pavements for speed warnings (e.g., entrance feature at change from rural to commercial area, entrance curve on ramp, two-lane roadway)

2. animated eyes on warning signs in advance of crosswalks to prompt motorists to watch for pedestrians

3. offset pedestrian crossings on divided highways with the use barriers to cause a pedestrian to turn in the direction of the oncoming traffic

4. automated pedestrian detection and green phase extension technologies

5. zig-zag pavement markings on the approaches to mid-block pedestrian crossings

6. messages painted on the pavement ("horizontal signing"), to include highway route numbers, stop and yield markings, traffic or parking prohibitions, bus lanes, school zones, lane markings carried through intersections, and dotted edgelines through exit and entrance ramps at interchanges

7. a "Look Left/Right" message marked on the street at pedestrian crossings to remind pedestrians to look for motor vehicles before stepping into the street

8. optical speed bars to warn of a hazardous area (transverse lines configured such that the spacing between the lines decreases as the hazard is approached, thus creating an optical illusion of acceleration to the driver and the impression of traveling faster than intended)

9. chevrons and dots to indicate proper vehicle spacing

10. stop signs equipped with red flashing light-emitting diodes (LEDs) embedded at each corner

11. colored electronic international symbols for warning messages on changeable message signs

12. pulsing white lights to notify motorists of an active work zone.

In September 2005, the VTRC researchers presented the results of this investigation to VDOT's central office and district traffic engineers, giving particular emphasis to the 12 measures identified as having potential for piloting. The traffic engineers were asked to identify the measures they were interested in as well as possible locations for piloting. Based on their input, 2 of the measures were selected for piloting: a stop sign equipped with flashing LEDs at each corner and optical speed bars. The results of this pilot study were documented in *Evaluation of Best Practices in Traffic Operations and Safety, Phase I: Flashing LED Stop Sign and Optical Speed Bars*.[10] Subsequent to this study, in 2008, district traffic engineers from VDOT's Northern Region Operations (NRO) Office requested that another measure be piloted: zig-zag pavement markings on approaches to mid-block pedestrian crossings.

Under the auspices of the FHWA's International Technology Scanning Program, a team of 10 U.S. traffic engineers traveled to Europe in May 1998 to observe innovative traffic control practices and identify those that could be implemented in the United States. In England, team members observed a unique means of informing drivers that they were approaching a pedestrian crossing: zig-zag pavement markings (shown in Figure 1). The purpose of these markings is to provide motorists an additional warning of an upcoming crosswalk. They also indicate no parking areas and overtaking prohibition zones.

VDOT expressed interest in this pavement marking treatment because of the many mid-block locations in the counties of Fairfax and Loudoun where the multiuse Washington and Old Dominion (W&OD) Trail crosses a highway. In 1987, the W&OD Trail was designated a National Recreation Trail by the U.S. Department of the Interior and is a very popular recreation destination for bicyclists, walkers, and runners. It is also used regularly by bicyclists and pedestrians as a route from home, direct or via the Washington Metro, to work and to shopping. Between 2 and 3 million people use it each year, thus making the W&OD one of the most successful rail-trails in the nation.[11]

There are more 70 highway crossings of the 45-mile W&OD Trail, which creates significant potential for serious crashes between vehicles and bicyclists/pedestrians, and there

Figure 1. Zig-zag Pavement Markings in England Observed by U.S. Traffic Engineers. From Scott Wainwright.

have been a number of such crashes. From 2002 to 2008, there were 21 bicycle- and 2 pedestrian-related crashes at 11 of the crossing locations. In April 2009, in an attempt to enhance safety at 2 of the crossing locations, VDOT installed zig-zag pavement markings in Loudoun County where the W&OD Trail crosses Belmont Ridge Road and Sterling Boulevard. Because zig-zag markings are not included in the *Manual on Uniform Traffic Control Devices* (MUTCD),[12] a Request for Experimentation was submitted to FHWA and approval was granted (see Appendix A).

PURPOSE AND SCOPE

The purpose of this study was to assess the effectiveness of the zig-zag pavement markings installed in advance of the W&OD Trail crossings at Belmont Ridge Road and Sterling Boulevard in Loudoun County, Virginia. Effectiveness was defined in three ways:

1. *An increase in motorist awareness in advance of the crossing locations*. Awareness was measured by computing the difference in vehicle speeds before, 1 week after, 6 months after, and 1 year after the installation of the zig-zag pavement markings.

2. *A change in motorist attitudes*. Attitudinal changes were measured using an electronic survey distributed to residents in Loudoun County that asked whether the markings had affected their awareness of the crossing, behavior, and tendency to yield.

3. *Motorist understanding of the markings*. Understanding was measured with another, more widely distributed survey that asked whether recipients correctly understood the purpose of the markings.

METHODS

To achieve the purpose of the study, five tasks were undertaken:

1. Review the literature.
2. Select sites, install pavement markings, and collect data.
3. Develop and distribute surveys.
4. Analyze field and survey data.
5. Develop recommendations.

Literature Review

A review of the literature was undertaken to obtain relevant information regarding zig-zag installations overseas and elsewhere in North America. Of particular interest were analyses of the zig-zag markings, either qualitative or quantitative; installation guidelines such as when and where to place the markings; and design features (e.g., horizontal and longitudinal dimensions). Other literature was also reviewed that pertained to motorists; bicyclists; pedestrians; pedestrian human factors, statistics, and interactions; and traffic control methods to improve the interactions among each of these transportation system users. Resources used to perform this task were the VDOT Research Library, the University of Virginia library, and relevant Transportation Research Board databases.

Site Selection, Pavement Marking Installation, and Data Collection

The following describes the criteria used for the selection of sites, the logic used for the design of the zig-zag pavement markings, procedures for installation of the pavement marking, and quantitative data collection methods.

Site Selection

A candidate list of sites was developed via discussions with VDOT NRO staff. Criteria were geared toward the pedestrian, bicycle, and vehicle crash history at the crossings; roadway geometry; posted speed limits; traffic volumes; and other factors that might influence data collection efforts such as access points, residential/business developments, proximity to intersections, signal density, etc. Of the 70 plus W&OD Trail / roadway intersections, 11 were identified as the best candidates. Upon site visits to each, it was determined that Belmont Ridge Road and Sterling Boulevard were the best locations for the pilot. Although pedestrian and bicycle crashes were relatively low at these two locations, it was determined that other safety considerations, primarily vehicle crash history, roadway geometry, trail volume, and traffic volume, constituted a high potential for crash risk.

Belmont Ridge Road

Belmont Ridge Road is a two-lane secondary road with a speed limit of 45 mph that runs in a general north/south direction. At its northern-most terminus is Route 7, which is approximately 1.3 miles north of the W&OD Trail crossing. The facility is rated as having a level of service (LOS) D and carries an average daily traffic (ADT) of 17,800 vehicles with a driver population of mostly commuters. Approximately 10 percent of the vehicle volume is heavy trucks attributable in part to rock quarry and concrete plants nearby.

The geometry of Belmont Ridge Road consists of downhill grades on both the north and south approaches to the crossing. Figure 2 shows the road profile in relation to the W&OD Trail crossing. The sight distance of the W&OD Trail crosswalk on the northbound and southbound approaches is approximately 660 and 1,750 feet, respectively. As opposed to the southbound approach, which has a relatively straight line of sight to the crossing, the northbound approach has a horizontal curve that decreases the viewing distance of the crossing. In advance of the crosswalk, warning signs of the trail crossing are located 600 and 690 feet from the crosswalk in the northbound and southbound approaches, respectively. In addition, warning signage with arrow placards is located at the crossing facing both approaches (shown in Figure 3).

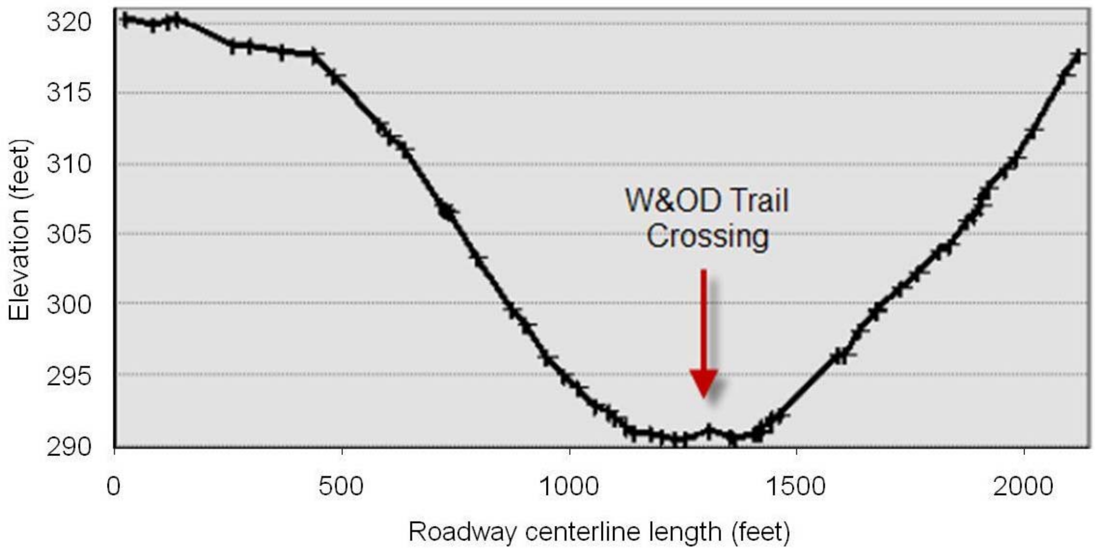

Figure 2. Road Profile of Belmont Ridge Road in Relation to W&OD Trail Crossing

Figure 3. Trail Warning Signs at Belmont Ridge Road W&OD Crossing

The W&OD Trail, which runs in an east/west direction in relation to Belmont Ridge Road, has yellow skip lines that run down the centerline of the trail. As the trail approaches the road crossing in both directions, the skip lines become solid lines. In addition to the centerline, other pavement markings on both approaches of the trail include advance rumble strips, stencils of "ROAD XING" and "STOP," and a STOP bar. Signage on the trail includes an advance STOP warning sign and double STOP signs with placards stating "REQUIRED BY LAW." A high-visibility zebra crosswalk exists where the trail crosses Belmont Ridge Road. Photographs of the advance warning signs on Belmont Ridge Road and W&OD Trail pavement markings and signage are provided in Appendix B.

Sterling Boulevard

Sterling Boulevard is a divided four-lane secondary road with a speed limit of 40 mph that runs in a general east-northeast / west-southwest direction. It is bounded by Route 28 at its western terminus and Route 7 at its eastern terminus. These roads are approximately 1 and 2.5 miles, respectively, from the W&OD Trail intersection. The facility has an LOS D rating and carries an ADT of 30,800 vehicles with a driver population of mostly commuters. Approximately 2 percent of the vehicle volume is heavy trucks.

The grade at Sterling Boulevard is relatively flat, although there is a slight crest on both the eastbound and westbound approaches to the trail crossing location. Figure 4 shows the road profile in relation to the W&OD Trail crossing. The sight distance of the crosswalk on the eastbound and westbound approaches is approximately 410 feet and 300 feet, respectively. These sight distances are compromised because of the roadway geometry. In advance of the crosswalk, warning signs of the trail crossing are located 450 and 360 feet from the crosswalk in the eastbound and northbound approaches, respectively. In addition, warning signage with an arrow is located at the crossing facing both approaches (shown in Figure 5).

The W&OD Trail, which runs generally in a west-northwest / east-southeast direction in relation to Sterling Boulevard, has the same pavement markings and signage as it does at Belmont Ridge Road with one slight difference. Instead of a double STOP sign at the trail/road intersection, there is a single STOP sign with a placard stating "REQUIRED BY LAW." Photographs of the advance warning signs on Sterling Boulevard and the W&OD Trail pavement markings and signage are provided in Appendix C.

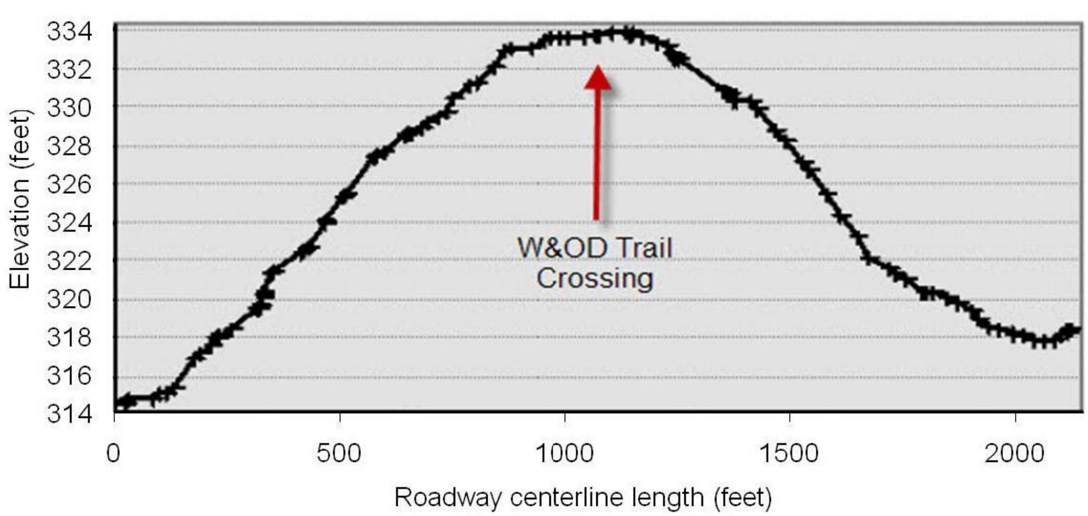

Figure 4. Road Profile of Sterling Boulevard in Relation to W&OD Trail Crossing

Figure 5. Trail Warning Signs at Sterling Boulevard W&OD Crossing

Zig-zag Design and Pavement Marking Installation

This section describes the designs chosen for the zig-zag pavement markings, including horizontal and longitudinal dimensions at Belmont Ridge Road and Sterling Boulevard, and procedures for installing the markings. The literature documented many various designs and layouts for zig-zag markings, as is discussed later. It is important to note that designs found in the literature are purpose specific (i.e., parking prohibition versus advance warning) and site specific (i.e., based on roadway geometries, access points, intersection densities, etc.).

Zig-zag Design for Belmont Ridge Road

Because Belmont Ridge Road is a two-lane facility, and potentially to maximize effectiveness, VDOT NRO management determined that the zig-zag lines should run down the center of each lane. There were essentially four design parameters that had to be determined: (1) the longitudinal zig-zag period (span of one zig-zag set); (2) the longitudinal span (how far the zig-zag markings extended from the crosswalk); (3) the striping width; and (4) the lateral span (horizontal span) of the markings. Design standards in Australia[13] were adopted for determining the longitudinal zig-zag period. The matching criteria for the other three design parameters were posted speed limit, visibility, and vehicle wheel span, respectively. Upon site visits, VDOT NRO staff determined that the zig-zag pavement markings should be clearly visible well before the crosswalk is visible. As previously discussed, the intention of the markings is to increase motorist awareness of the W&OD crossing and when the posted speed limit was considered, this could be achieved only if the markings extended a substantial distance from the crosswalk. When speed, the horizontal curvature on the northbound approach, and the advance warning sign location was taken into account, it was determined that the markings should extend 500 feet from the crosswalk. In addition, it was determined that the markings should be "tied" (or connected) to the crosswalk markings so motorists could associate the zig-zag markings with the W&OD Trail crossing. For uniformity purposes, 500 feet was also chosen for the southbound approach. Figure 6 shows an aerial view of the length of the markings in relation to the W&OD Trail crossing and warning signage.

As with most secondary roads in Virginia, the edgeline and centerline markings on Belmont Ridge Road are 4 inches in width. To increase the visibility of the zig-zag markings (and possibly the "awareness" of motorists), the striping width was chosen to be 6 inches. The dimension of the lateral span of the markings was chosen to be 4 feet. This decision was made so that the span of vehicle wheel track widths would clear the zig-zag markings, thus preventing accelerated wear of the zig-zag points (where lines intersect).

Figure 7 is a schematic of the final zig-zag design chosen for the northbound approach to the W&OD Trail (the design of the southbound markings approaching the crosswalk was identical).

Zig-zag Design for Sterling Boulevard

The same parameters for the zig-zag marking design on Belmont Ridge Road were addressed at Sterling Boulevard, i.e., the longitudinal span, striping width, and lateral span of the markings. However, because of differences in the lateral geometry of the roadways (Sterling Boulevard is a divided four-lane facility) and in the interest in testing a different zig-zag pattern, two of the three matching criteria were different. The zig-zag pattern chosen for this location was similar to some zig-zag installations in Europe (see Figure 1); where zig-zag markings run along the centerline and edgelines of roadways.

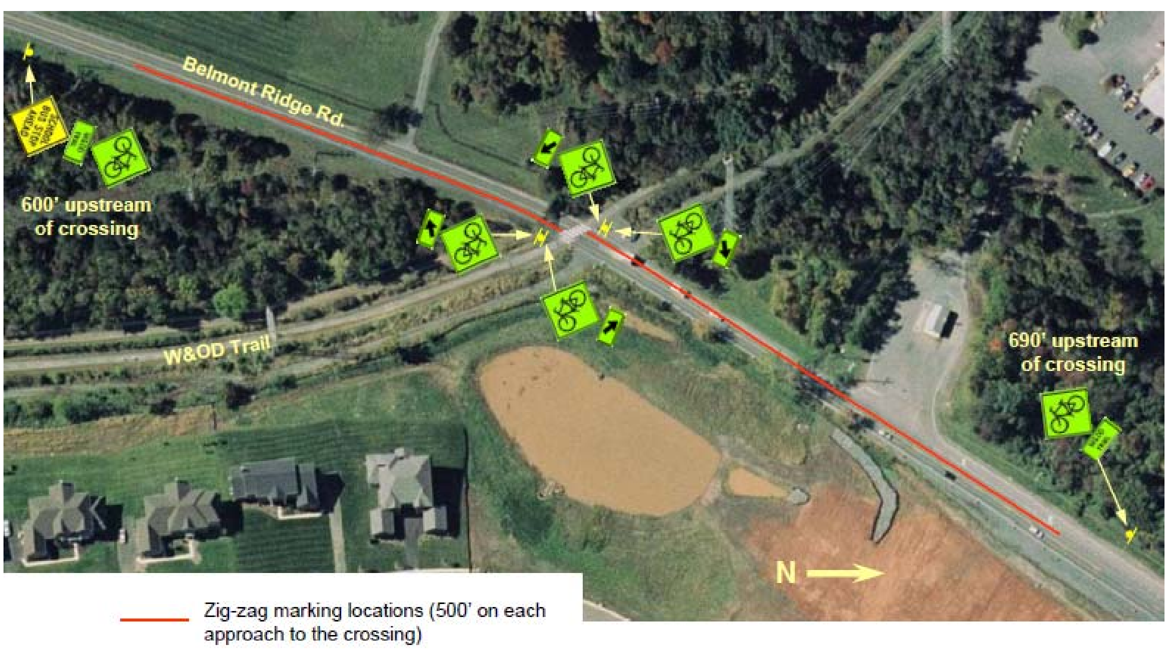

Figure 6. Aerial View of Belmont Ridge Road Showing W&OD Trail Warning Sign Locations and Longitudinal Zig-zag Dimensions

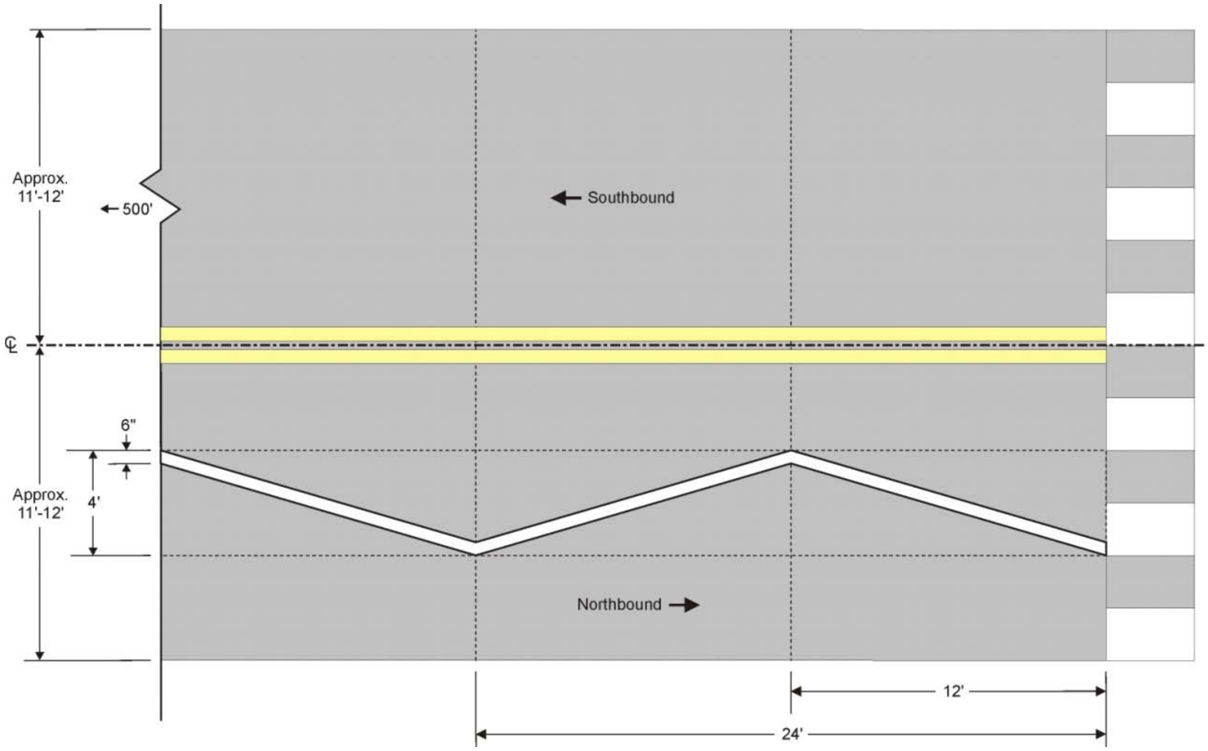

Figure 7. Schematic of Zig-zag Design Chosen for Belmont Ridge Road

Speed limit was used as a factor for determining the length of the markings. As previously discussed, the W&OD Trail crosses at a vertical crest on the roadway (see Figure 4), which inhibits the viewing distance to the crosswalk markings. Therefore, to provide motorists a visual cue before they see the crosswalk markings, 500 feet was chosen as the longitudinal length of the zig-zag markings.

In terms of the lateral span and striping dimensions, it was decided to use a 2-foot lateral span for each zig-zag pattern and a 4-inch width for the markings. The 2-foot lateral span was chosen so that the markings running along the centerline and edgelines of the roadway were outside vehicle wheel track widths (thus preserving the markings). The 4-inch striping width was chosen to provide a more prominent zig-zag (i.e., 4-inch lines through a 2-foot span makes for a sharper angle than a 6-inch line through a 2-foot span). In addition, existing edgelines and centerlines are 4 inches in width; therefore, because the zig-zag lines were replacing those lines, is was deemed appropriate to match these widths.

Figure 8 is a schematic of the final zig-zag design chosen for the eastbound approach to the W&OD Trail. It should be noted that the initial intention was to create a yellow zig-zag line along the left edgeline; however, the type of pavement marking material required for this application was unavailable. Maintaining a yellow edgeline was important, and therefore zig-zag markings were not installed along the left edge of the roadway. In the westbound direction, curb and gutter tapers reduce the lane widths on the approach to the crosswalk. Thus, to maintain an appropriate width throughout the travel lanes, no zig-zag markings were installed along either the

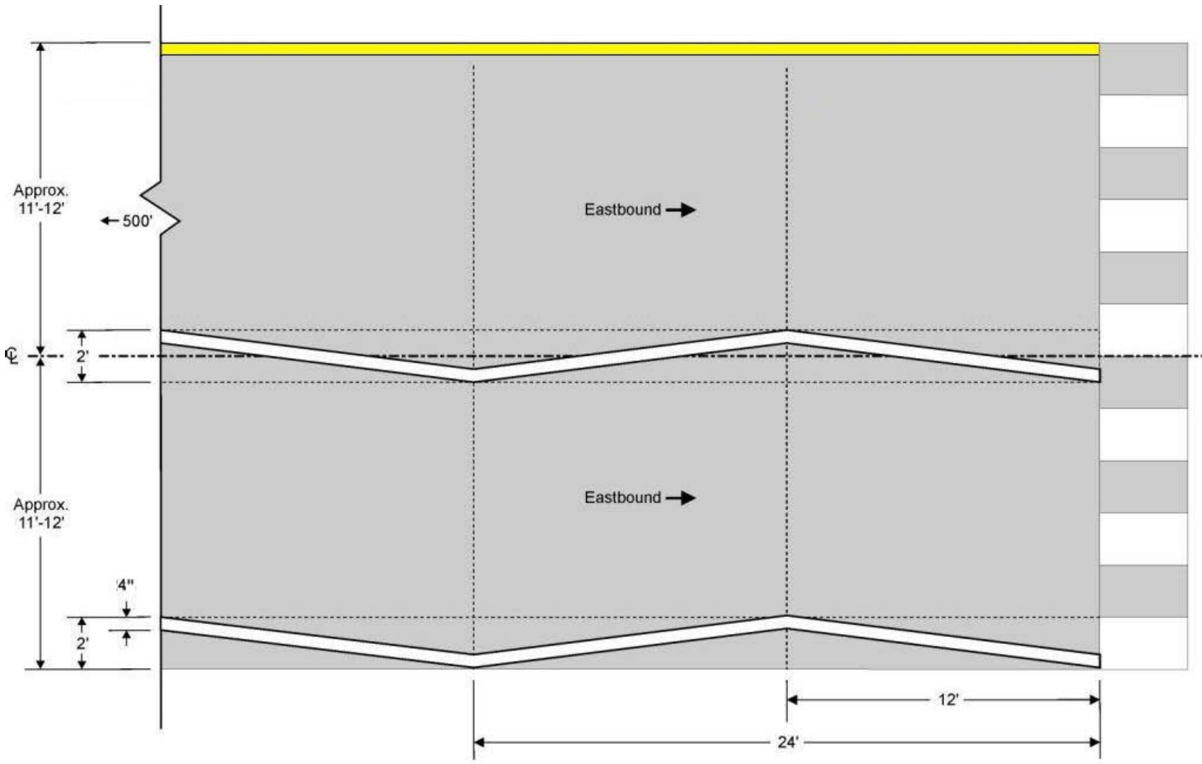

Figure 8. Schematic of Zig-zag Design Chosen for Eastbound Approach of Sterling Boulevard

left or right edgeline of the roadway. Figure 9 shows an aerial view of the length of the markings on each approach in relation to the W&OD Trail crossing and warning signage.

Marking Installations at the Two Crossings

The zig-zag pavement markings on Belmont Ridge Road and Sterling Boulevard were installed on April 13 and 23, 2009, respectively. This task included eradication of existing centerlines and edgelines (at Sterling Boulevard only), layout of the markings using chalk lines, and application of the markings. The markings were applied using a paint cart that placed white thermoplastic pavement marking material with reflective beads at a thickness of 90 mils. The marking procedure at Belmont Ridge Road lasted approximately 3½ hours. The marking procedure at Sterling Boulevard took 1 hour longer because of the eradication procedure on both centerlines and the right edgeline on the eastbound approach. Figures 10 and 11 show the zig-zag markings upon completion of the application at Belmont Ridge Road and the eastbound approach at Sterling Boulevard, respectively. Additional photographs of the zig-zag marking layout and installation at both test sites are provided in Appendix D.

Data Collection

The data collection plan included a “before and after” study at the Belmont Ridge Road and Sterling Boulevard W&OD crossings. The purpose of the zig-zag markings was to raise motorist awareness of the upcoming crossings, and therefore the primary measure of effectiveness was vehicle speed. Speed reductions signify a positive motorist reaction in terms of safety benefits to trail users. Speed data were collected using automatic traffic recorders

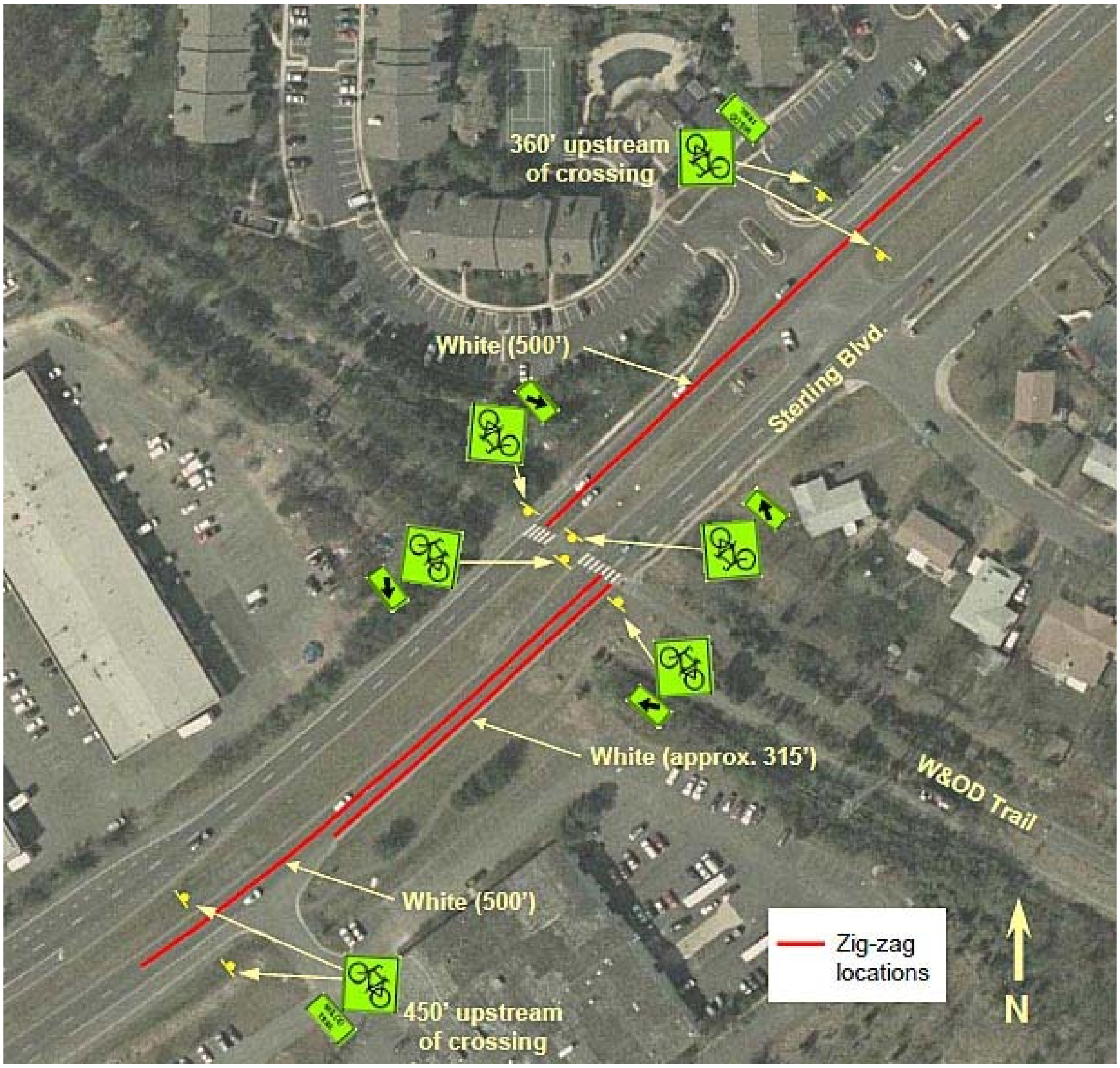

Figure 9. Aerial View of Sterling Boulevard Showing Locations of W&OD Trail Warning Signs and Longitudinal Zig-zag Dimensions

(ATRs) before the markings were installed, immediately after installation (within 1 week), 6 months after, and 1 year after installation. One-week after data were collected to account for and assess the extent of a "novelty effect" where mean speeds may initially decrease but over time rebound back to baseline (before) levels. These data were deemed important because they provide information regarding the long-term effect of the markings on non-local drivers.

To account for possible systematic variations in traffic patterns and travel speeds over the 1-year study period, average speeds and vehicle volumes at two control sites were evaluated with ATRs in conjunction with the study sites. The control sites chosen were Hirst Road in Loudoun County and Sunrise Valley Drive in Fairfax County. These locations have geometric and traffic characteristics analogous to those at Belmont Ridge Road and Sterling Boulevard, respectively.

Figure 10. Zig-zag Markings at Belmont Ridge Road

Figure 11. Zig-zag Markings on Eastbound Approach at Sterling Boulevard

Because the primary safety concern at the crossings is the potential for conflicts between motor vehicles and pedestrians/bicyclists, speeds were also collected with a pedestrian and/or bicyclist present at both study sites during the same before and after time intervals as the ATR data collection effort. To do this, speeds of approaching vehicles were measured with a light detection and ranging (LIDAR) gun when a bicyclist and/or pedestrian was stopped at the edge of the roadway waiting to cross.

Crash data were also analyzed 5 years prior to the installation of the zig-zag markings and 1 year after installation. Data were obtained on pedestrian/bicyclist related crashes and vehicle-to-vehicle crashes from FR-300 crash report and Loudoun County police databases. It was deemed important to document vehicle-to-vehicle crashes because if the zig-zag markings altered the yielding tendency and speeds of motorists, a greater potential for such crashes might exist.

Speeds Obtained with Automatic Traffic Recorders

Prior to the installation of the zig-zag markings, Nu-Metrics counters (Model No. NC-97) were installed to collect “before” vehicle volume and speed data at specific locations along each approach lane at each study site. These counters are flat disks that are nailed into the pavement and use vehicle magnetic imaging technology to detect vehicle count, speed, and classification. To obtain reasonable datasets and speed profiles, a determination was made to install the counters at four locations upstream of the crosswalk in each lane at each study site. On each approach, these locations were at (1) a distance where the zig-zag markings could not be seen, (2) the beginning of the markings, (3) the longitudinal middle of the markings, and (4) the end of the markings (at the crosswalk). Upon completion of the before data collection effort, the data were reviewed for the purposes of analyzing data integrity and constructing volume profiles. Constructing volume profiles served two purposes: (1) identifying peak, mid-peak, and off peak flows for use when analyzing “after” data, and (2) creating baseline traffic volume profiles so that systematic differences in traffic characteristics could be examined throughout the study period. The counters were then re-installed at the same locations immediately after, 6 months after, and 1 year after installation of the markings.

Belmont Ridge Road. On the northbound approach of Belmont Ridge Road, the distances for each counter location were 850, 500, 250, and 0 feet from the crosswalk. On the southbound approach, the counters were located 2,000, 500, 250, and 0 feet from the crosswalk. In the before period, speed data were obtained on Tuesday, September 30, through Thursday, October 2, 2008. Figure 12 shows the average before traffic volume profiles for the northbound and southbound approaches. From these curves, it was determined that the highest northbound traffic volumes occurred between 4 P.M. and 7 P.M. and the highest southbound traffic volumes occurred between 7 A.M. and 9 A.M. In addition, mid-peak volumes (medium volumes) were determined to be between 11 A.M. and 1 P.M., and off-peak volumes (low volumes) were determined to be between 7 P.M. and 7 A.M. for both directions, respectively. Determining these levels of volume (high, medium, low) was important because data were analyzed for each of these levels after the zig-zag markings were installed.

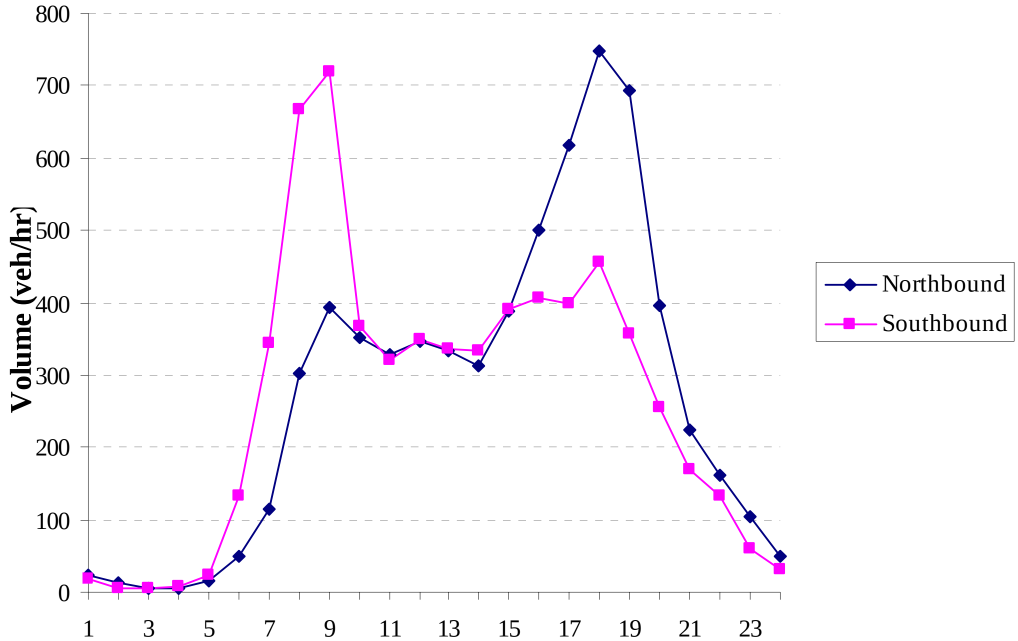

Figure 12. Average "Before" Traffic Volumes on Belmont Ridge Road

Immediately after the zig-zag markings were installed, data were collected for a 4-day period commencing on Monday, April 13, and ending on Thursday, April 16. To remain consistent with the before data collection days, only the data from Tuesday through Thursday were used in the evaluation. The 6-month after data collection effort occurred Tuesday, October 6, through Thursday, October 9, 2009, and the 1-year after data collection effort occurred Tuesday, April 6, through Thursday, April 8, 2010. For each data collection period, eight ATRs were installed (4 northbound and 4 southbound); thus a total of 32 datasets were analyzed for Belmont Ridge Road.

Sterling Boulevard. On the eastbound approach of Sterling Boulevard, the locations for ATR installations were at distances of 2,000, 500, 250, and 0 feet from the crosswalk. On the westbound approach, the locations were at distances of 2,300, 500, 250, and 0 feet from the crosswalk. Because there are two lanes per direction, two ATRs were installed at each distance (one in each lane). In the before period, speed data were obtained Tuesday, September 30, through Thursday, October 2, 2008. Figure 13 shows the average before traffic volume profiles for both approaches. From these curves, it was determined that the highest eastbound traffic volumes occurred between 4 P.M. and 7 P.M. and the highest westbound traffic volumes occurred between 7 A.M. and 9 A.M. In addition, mid-peak volumes (medium volumes) were determined to be between 12 P.M. and 1 P.M., and off-peak volumes (low volumes) were determined to be between 7 P.M. and 7 A.M. for both directions, respectively.

Five days after the zig-zag markings were installed, data were collected for a 3-day period from Tuesday, April 28, through Thursday, April 30, 2010. The 6-month after data were collected from Tuesday, October 6, through Thursday, October 9, 2009, and the 1-year after data from Tuesday, April 6, through Thursday, April 8, 2010. For each data collection period, 16 ATRs were installed (8 eastbound and 8 westbound); thus, a total of 64 datasets were analyzed for Sterling Boulevard.

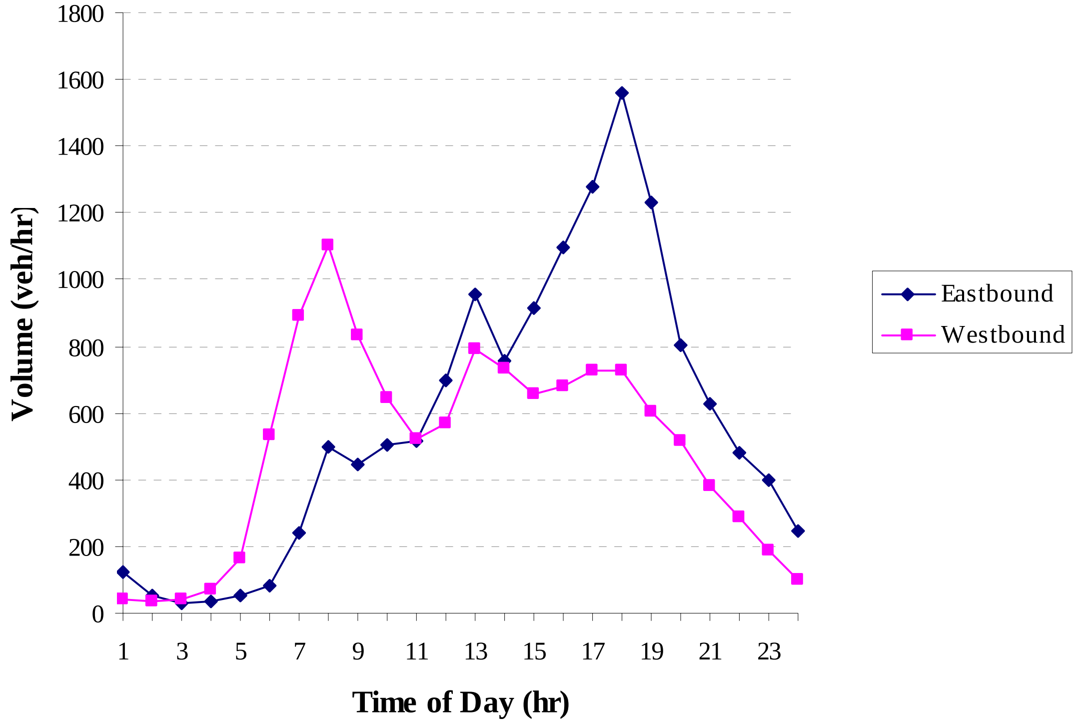

Figure 13. Average "Before" Traffic Volumes on Sterling Boulevard

Control Sites. Similar ATR data collection procedures were performed at the control sites. As previously discussed, the main intent of monitoring a different set of roadways was to account for possible systematic changes in area traffic characteristics over the study period. Hirst Road, a two-lane facility with a posted speed limit of 45 mph, was chosen as the control site for Belmont Ridge Road. Sunrise Valley Drive, a four-lane divided roadway with a 35 mph speed limit, was chosen as the control site for Sterling Boulevard. The control sites were chosen because both have W&OD crossings, similar geometric, and traffic characteristics and both are in close proximity to their respective test sites. ATR data collection at the control sites was similar to that at the test sites except only one direction of travel was evaluated over three time periods (before, 6 months after, and 1 year after). Further, because zig-zag markings were not installed at these locations, only three distances were chosen for ATR installations: 500, 250, and 0 feet from the crosswalk.

Speeds Obtained with LIDAR Gun

Data obtained with the ATRs provided average speeds over a 3-day period. Although these data encapsulated a broad overall picture of motorist reaction when traversing over the zig-zag markings (in terms of speeds), they did not allow for a targeted analysis of motorist reaction when a pedestrian or bicyclist was at the crosswalk waiting to cross. Therefore, to capture vehicle speeds in such a scenario, staged pedestrians were positioned at the crosswalk/roadway interface and individual vehicle speeds were obtained with a LIDAR gun by an upstream observer as vehicles progressed toward the crosswalk at both Belmont Ridge Road and Sterling Boulevard. The objective was to track vehicles in a free flow state (i.e., vehicles not impeded or influenced by other vehicles) on their approach to the crossings. Therefore, vehicles were not tracked if (1) it was determined that a leading vehicle was influencing the speed of a candidate vehicle and (2) if a vehicle or vehicles were queued at the crosswalk thus potentially influencing the approach speed of a candidate vehicle. Data were collected via a laptop equipped with a laser data transfer program. While a vehicle was tracked, its speed, range (distance from the LIDAR gun), and time (to the nearest 100th of a second) were recorded. The LIDAR gun has the capability of recording data approximately every 0.3 second. At each approach, vehicle speeds were recorded for approximately 1½ hours during non-peak hours so as to lessen the potential for candidate vehicles to be affected by leading vehicles.

It was important that the observer with the LIDAR gun had a clear view of the crosswalk and was able to track vehicles before they entered the zig-zag marking zone through to the crosswalk markings. On the northbound approach of Belmont Ridge Road, the observer was positioned 550 feet upstream of the crosswalk. Ideally, this distance would have been longer to obtain more data prior to vehicles entering the zig-zag zone, but the horizontal curvature obscured the view of the crosswalk. On the southbound approach, the observer had a clear view of the crosswalk from a much longer distance and therefore was able to be positioned 1,200 feet upstream of the crossing location.

On the eastbound approach of Sterling Boulevard, the observer was located 330 feet upstream of the crosswalk. Observer locations further upstream were unattainable because of the roadway geometry and lack of suitable locations for maintaining inconspicuousness. On the westbound approach, the observer was located 630 feet upstream of the crosswalk. In each direction, the majority of the data collected with the LIDAR gun were of vehicles progressing in the right lane. This was because vehicles in the right lane often obscured the view of vehicles in the left lane.

Development and Distribution of Surveys

To gauge opinions of the zig-zag markings, two types of surveys were administered. One year after the zig-zag marking installation, a survey developed through SurveyMonkey targeting motorists, pedestrians, and bicyclists familiar with the markings was distributed via web links on the website of the Loudoun County Government and via electronic newsletters distributed by the Broad Run and Sterling District supervisors' offices (respective districts for Belmont Ridge Road and Sterling Boulevard). Web and email links to the survey were also distributed to bicycle clubs operating throughout the Northern Virginia area including Bike Loudoun, the Potomac Pedalers Touring Club, the Washington Area Bicyclists Association, Fairfax Advocates for Better Bicycling, and the Reston Bicycle Club. In addition, on-site surveys were administered to users of the W&OD Trail at both Belmont Ridge Road and Sterling Boulevard.

Two subject groups were targeted in the surveys: (1) subjects who had driven over the zig-zag markings, and (2) subjects who had used the W&OD Trail at Belmont Ridge Road and/or Sterling Boulevard. General questions were also posed to both subject groups. Examples of questions specific to motorists included:

- Have the zig-zag markings altered your driving behavior?

- Do you agree or disagree that the zig-zag pavement markings increase your driving awareness or attention?

- When bicyclists and/or walkers are waiting to cross at the crosswalk, have the zig-zag pavement markings increased, decreased, or had no impact on your tendency to yield?

- From a motorist perspective, do you think the zig-zag markings increase safety, have no impact on safety, or decrease safety for bicyclists and walkers?

Examples of questions specific to trail users included:

- What effect do you think the zig-zag pavement markings have had on the driving behavior of motorists?

- Since the zig-zag pavement markings were installed, have you witnessed a tendency for more vehicles to yield to bicyclists and walkers at the crossing than before?

- From a trail user perspective, do you think the zig-zag markings increase safety, decrease safety, or have no impact on safety for bicyclists and walkers?

Examples of generic questions posed to both motorists and trail users included:

- Have you heard or read news reports about the zig-zag pavement markings?
- In your opinion, why do you think VDOT installed the zig-zag pavement markings?
- In your opinion, who has the right-of-way (right to go first) at the trail crossings?

In addition to this survey, a different type of survey was distributed at “off-site” locations targeting motorists unfamiliar with the W&OD crossing locations at Belmont Ridge Road and Sterling Boulevard. This survey was conducted at the Charlottesville office of the Virginia Department of Motor Vehicles and VDOT rest areas off I-64 in Waynesboro and I-81 in Staunton. The primary objective of this survey was to gauge whether or not the general motorist population understands the purpose (or meaning) of zig-zag markings. The survey asked subjects to look at a picture of the zig-zag markings with no context (i.e., no crossing signage or crosswalk visible) to ascertain if they understood the purpose of the markings. Once this question was answered, the subjects viewed a picture of the zig-zag markings with context (i.e., crossing signage and crosswalk visible). Subsequently, they were again asked if they understood the purpose of the zig-zag markings. Comparisons of the responses were then made.

RESULTS

Literature Review

In 2008, 4,378 pedestrians and 716 bicyclists were killed in traffic crashes in the United States. In addition, 69,000 pedestrians and 58,000 bicyclists were injured in traffic-related crashes.[14,15] Most of the fatalities and injuries were the result of conflicts with motor vehicles. A study performed by the National Highway Traffic Safety Administration documented the risks pedestrians and bicyclists encounter on roadways attributable to motorist behavior. Seven percent of crashes studied were the result of driver inattentiveness, 9 percent failure to yield the right-of-way, 10 percent driving too fast, and 4 percent operating vehicle in a reckless manner.[16]

Findings from focus group sessions by Redmon[17] revealed that in the Washington, D.C., area, pedestrians and motorists had no clear understanding of the laws regarding pedestrians' right-of-way. This ambiguity translated into pedestrians feeling unsafe in crosswalks because of (1) their fear that motorists might not be aware of or looking for pedestrians, and (2) motorists concerned about pedestrians not paying attention to traffic and pedestrian road signs. Ullman et al.[18] corroborated these concerns by concluding that the unpredictability of drivers with regard to yielding was the main concern of pedestrians. Zegeer et al.[4] further corroborated these concerns by concluding:

- Higher pedestrian volumes, higher ADT rates, and a greater number of roadway lanes are related to a higher incidence of pedestrian crashes.

- Crosswalk location, speed limit, direction of traffic flow, crosswalk condition, and crosswalk marking pattern were not related to the incidence of pedestrian crashes.

- The presence of a median decreased the pedestrian crash risk.

- Marked crossings had a higher incidence of pedestrian crashes on multilane (four or more lanes) roads with high ADTs.

- Marked and unmarked crossings had similar incidences of pedestrian crashes on all two-, three-, and multilane roads with lower ADTs.

- Pedestrians aged 65 and older were over-represented in crashes.

- The installation of marked crossings did not alter motorist behavior (e.g., stop or yield to pedestrians) or pedestrian behavior (e.g., crossing without looking).

With respect to motorist reaction, Katz et al.[19] found that drivers stop more frequently when the vehicle's approach speed is low, when the pedestrian is in a marked crosswalk, when the distance between vehicle and pedestrian is greater rather than less, when pedestrians are in groups, and when the pedestrian does not make eye contact with the driver. In terms of vehicle-to-vehicle collisions, Yagar[20] reported a higher incidence of rear-end crashes at intersections immediately after crosswalk markings were installed. The study also documented that most of the crashes involved out-of-town drivers.

In an attempt to alleviate crash risk, many localities and state departments of transportation (DOTs), including VDOT, have developed guidance with respect to installing crosswalks at both uncontrolled (e.g., mid-block) and controlled (e.g., intersections) locations. The primary factors used to develop the guidelines are typically number of lanes, ADT, and speed. At locations where crosswalks alone are insufficient, other treatments, or a combination of treatments, are recommended. Dougald[21] documented some of the treatments presented in Virginia's guidelines which include:

- raised crosswalks
- rumble strips
- refuge islands
- split pedestrian crossovers
- bulb-outs
- overhead signs and flashing beacons
- in-roadway warning lights
- pedestrian-actuated signals
- grade-separated crossings.

Within the last decade, some localities and DOTs in the United States and abroad have used perceptual countermeasures in the form of innovative pavement markings in an attempt to influence driver behavior for the purposes of creating safer driving environments. For example, transverse lines that run across roadways (either evenly spaced or staggered) have been used for speed reduction on high-speed facilities in the United Kingdom[22] and have been studied in the United States.[10] Peripheral transverse lines (or hatch lines) installed along edgelines have been used in the United States[23] and Australia[24] as traffic calming measures at curves on low-speed facilities, rural roads, and approaches to intersections. This traffic calming measure is also included in VDOT's current *Traffic Calming Guide for Local Residential Streets.*.[25] A variation of peripheral transverse lines is used in Hawaii where markings referred to as "shark's teeth" have been installed to reduce speeds on curves (see Figure 14).[26] Converging chevron markings

Figure 14. Shark's Teeth Pavement Markings Installed in Hawaii. From Ron Thiel. Reprinted with permission.

is another type of perceptual pavement marking used in the United Kingdom[22] to remind motorists to keep a safe distance from the vehicle in front of them and in the United States[27] to reduce speeds on high-speed ramps. To varying degrees, each of these types of pavement markings has been shown to have an impact on driver reaction in terms of speed reduction.

The Road and Traffic Authority's (New South Wales, Australia) *Road User's Handbook* noted that some pedestrian crossings have zig-zag lines marked on the road before the crossing to advise motorists that they are approaching a crossing that may be hidden because of a curve or crest or dip in the road.[28] Zig-zag pavement markings are another perceptual countermeasure used overseas to create safer driving environments by attempting to increase motorist awareness near crosswalks, prohibit parking, and/or prevent vehicle overtaking near such facilities. For example, the Road and Traffic Authority approved the use of zig-zag pavement markings at marked "foot crossings" as a supplementary advance warning device at difficult sites, specifically where sight distance is inadequate.[13]

The Confidence School of Motoring, located in Northern Ireland, noted that there are five types of pedestrian crossings: zebra, pelican, puffin, toucan, and pegasus. Drivers approaching all five types are made aware of the crossing of the upcoming crossing in part because of zig-zag road markings.[29] On the other hand, the Department of Main Roads in Queensland, Australia, has not approved the use of zig-zag pavement markings in advance of pedestrian crossings and has stated that they will not. Based on a review of local practices and the lack of support from some national agencies, it was concluded that

> it is essential to denote similar conditions with the same warning message, so that road users can readily anticipate the course of action required. To use unofficial, non-standard, and non-national warning messages (i.e., zig-zag markings) is confusing for both Queensland and interstate motorists driving on Queensland roads, and thus this practice creates a potentially hazardous situation, increasing the risk to pedestrians and motorists.[30]

In North America, two locations were found to have installed variations of zig-zag markings as a means to increase motorist awareness near crosswalks and STOP-controlled intersections. To encourage motorists to slow down near a school, the Traffic Division of Public Works in Hawaii installed the markings to capture the attention of motorists and reduce speeds as motorists approached the crosswalks at Kalanianaole School in PaPa'ikou. Zig-zag markings have also been applied at the residential intersections of Kekuanaoa and Kalanikoa; Kukuau and Mohouli; and Wilder and Puainako. Figure 15 shows the markings at Wilder and Puainako. Informal studies performed at these intersections showed that instances of crashes decreased after the markings were installed.[26]

In Ottawa, Canada, zig-zag markings were recently installed at three locations on a residential collector roadway. They were installed to help reduce speeds based on complaints from residents. Other treatments such as road narrowing devices were tried, but they did not have the effect residents wanted. Data are currently being collected, but no definitive quantitative information is available on the effectiveness of the markings in terms of speed reduction (S. Lyon, personal communication).

Figure 15. Zig-zag Pavement Markings at Intersection of Wilder and Puainako in Hawaii. From Ron Thiel. Reprinted with permission.

Overseas, zig-zag markings are used in Trinidad, the United Kingdom, New Zealand, Hong Kong, Singapore, and South Africa to restrict parking at pedestrian crossings. The European Transport Safety Council cited a study in which 33 percent of pedestrians reported that something made it difficult for them to see a striking vehicle. A similar proportion (40%) of drivers reported that something obstructed their sight to victim pedestrians. In both cases, a parked car was most cited as the obstructing object.[31,32]

In the United States and South Africa, zig-zag markings are used to restrict changing lanes and prohibit pedestrians from crossing within the zig-zag zone.[33] Incidences of pedestrian-vehicle conflict resulting from obstruction of a driver's line of sight are common at bus stops and at pedestrian crossings when an overtaking vehicle collides with a pedestrian crossing the road—also known as multiple-threat phenomenon.[32] In a study by Wilson,[34] zig-zag markings were installed on 30 roadways in Great Britain 19 meters on either side of zebra crossings to improve safety by prohibit vehicle overtaking on the approach and to warn pedestrians not to cross the areas marked by them. A before and after study revealed a 14 percent decrease in the proportion of pedestrians crossing within the zig-zag zone and a 20 percent decrease in the proportion of vehicles overtaking in the zig-zag zone after the zig-zag markings were installed.

For zig-zag markings to be effective, there needs to be a clear understanding of their intended purpose. As Mutabazi[32] stated: "the meaning of this control device has proven elusive to most road users and road safety stakeholders in some parts of the world." In Trinidad, where zig-zag markings are installed to prohibit parking, a survey revealed that zig-zag lines were the most common element misunderstood when persons were asked to indicate meanings of crossing features. Of the subjects, 1 percent indicated the correct meaning of no parking and 83 percent indicated the meaning as being either to slow down or to proceed with caution.[32]

In contrast to Trinidad, the practice in Australia is to mark zig-zag lines only along the centerline on approaches as an advance warning sign to zebra crossings. In July 1989, the Australian Road Research Board released a road user survey (undertaken in New South Wales, Victoria, and South Australia) on drivers' knowledge of traffic control devices and associated road rules. On the question of the meaning of the advance pavement markings ahead of pedestrian crossings that consist of the zig-zag line and the solid diamond marking, 65 percent of total respondents in all three states gave a range of responses including "No Parking," "Don't Know," and "Other Comments." Only 35 percent of total respondents gave the correct response: "Pedestrian Crossing Ahead." This percentage dropped to as little as 11 percent of respondents from South Australia as they were not using the zig-zag pavement marking in their state.[35]

The Trinidad and Australia surveys highlighted the potential confusion and motorists' lack of understanding of the message intended to be conveyed by a zig-zag pavement marking. This is in part due to the varying nature of their intended purpose (e.g., parking prohibition versus overtaking restriction versus advance warning). Mutubazi[32] maintained that more education and public information on crossing features and their intended purpose are needed to create safer and more effective crossing environments.

Data Collection

Speeds Obtained with Automatic Traffic Recorders

Vehicle speeds obtained with the ATRs at the two sites were collected as bin data. Prior to data collection, a decision to program the ATRs to collect bin data every hour was made. This allowed more days of data to be collected (capturing data every 30 or 15 minutes can exhaust the memory of the devices). Table 1 shows an example of the ATR speed bin output for a single day. Once data were obtained in the field, they were downloaded into an Excel spreadsheet. From this worksheet, bin data were extrapolated into discrete mean bin data points. For example, in Table 1, during the hour 16:00-17:00 (4 P.M.–5 P.M.) and the speed bin of 40 to 44 mph, there were 180 vehicles recorded. This dataset was expanded from 1 data point (150, 40-44) to 180 data points with an associated speed of 42.5 mph per data point. This process created larger datasets and allowed for more robust statistical comparisons of mean speeds.

The data "expansion" procedure was performed for each data collection day and study period (before, 1 week after, 6 months after, and 1 year after). Using the volume profiles as described in the "Methods" section (see Figures 12 and 13), the data were further reduced into categories of high volume, medium volume, and low volume. This was carried out to evaluate differences in mean vehicle speeds during varying traffic conditions (based on time of day). Analysis of variance was then performed on mean speeds from the data obtained at each ATR location, for each volume condition (high, medium, and low), and for each data collection period. Mean speed profiles for the high, medium, and low volume conditions exhibited similar trends at Belmont Ridge Road and Sterling Boulevard. Therefore, the results provided in this report include only data from the medium volume condition. The high and low volume conditions are shown in Appendices E and G.

Table 1. Example of ATR Data Output File

Time of Day	Speed Bin (mph)														
	0 to 9	10 to 14	15 to 19	20 to 24	25 to 29	30 to 34	35 to 39	40 to 44	45 to 49	50 to 54	55 to 59	60 to 64	65 to 69	70 to 74	75 to <
[00:00-01:00]	0	0	0	0	0	0	1	5	7	9	5	1	0	0	0
[01:00-02:00]	0	0	0	0	0	0	2	2	1	5	3	0	0	0	0
[02:00-03:00]	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0
[03:00-04:00]	0	0	0	0	0	1	0	2	2	1	0	0	0	0	0
[04:00-05:00]	0	0	0	0	0	0	1	2	2	5	2	1	0	0	0
[05:00-06:00]	0	0	0	1	0	2	1	9	18	16	1	0	1	0	0
[06:00-07:00]	0	0	0	1	1	0	2	32	37	27	10	4	2	0	0
[07:00-08:00]	0	1	1	1	3	11	46	87	82	58	21	3	0	0	0
[08:00-09:00]	0	2	0	3	6	25	72	102	93	40	11	5	3	0	0
[09:00-10:00]	0	0	0	0	0	6	31	88	94	46	10	3	0	1	0
[10:00-11:00]	0	0	0	0	2	5	43	81	94	35	15	3	2	1	0
[11:00-12:00]	0	0	0	1	1	16	24	85	122	52	12	2	0	1	0
[12:00-13:00]	0	1	0	2	2	6	33	95	116	65	11	2	0	0	0
[13:00-14:00]	0	0	2	0	1	5	24	84	107	65	14	5	1	1	0
[14:00-15:00]	0	0	1	1	6	4	47	123	116	43	17	2	2	0	0
[15:00-16:00]	0	2	1	2	3	15	54	146	155	69	30	13	5	0	0
[16:00-17:00]	0	5	2	3	1	8	42	180	200	105	27	5	2	2	1
[17:00-18:00]	0	1	2	0	6	33	100	246	229	117	34	16	1	0	1
[18:00-19:00]	0	2	1	0	3	16	68	145	237	110	38	7	5	1	1
[19:00-20:00]	0	1	0	0	2	4	22	90	141	78	27	3	0	0	2
[20:00-21:00]	0	1	3	1	1	10	25	77	85	32	4	2	0	1	0
[21:00-22:00]	0	1	0	0	2	4	17	35	42	30	10	0	1	1	0
[22:00-23:00]	0	0	0	0	0	2	5	32	27	21	12	2	0	0	0
[23:00-00:00]	0	0	0	0	0	0	3	9	14	18	2	0	0	0	0

Belmont Ridge Road

Figure 16 shows the mean speed profiles for the medium volume condition on the northbound approach of Belmont Ridge Road (the high and low volume conditions are shown in Appendix E). Each data point correlates with its respective ATR location upstream of the crosswalk (i.e., 850, 500, 250, and 0 feet), and each curve represents the time period when the data were collected (i.e., before, 1 week after, 6 months after, and 1 year after). Data points are not shown at the crosswalk (0 feet) during the before period and the 1-year after period because of poor data quality obtained from the ATRs. These missing data points compromised the ability to analyze fully the nature of northbound speeds at the crosswalk over the duration of the project. Further compromising the analysis on this approach was the apparent random scatter of the data points. Some of this “randomness” may be attributed to site geometry for which vehicle speeds on a horizontal and vertical curvature exhibit less uniformity. Notwithstanding the random scatter, a few key trends noted in this graphic are:

- At 850 feet from the crosswalk, mean speeds in the before and 1-week after period are essentially identical (45.3 and 45.5 mph, respectively). However, upon vehicles entering the zig-zag zone at 500 feet, mean speeds in the 1-week after period dropped by a statistically significant amount compared to the before speeds (Δ = 7.5 mph).

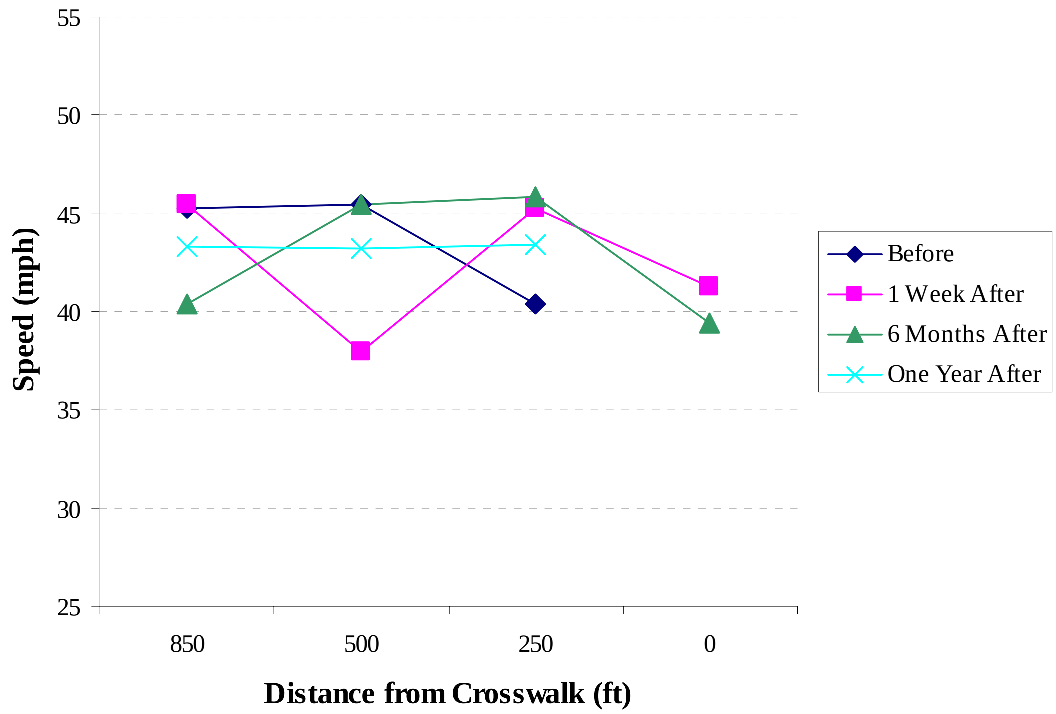

Figure 16. Mean Speed Profiles from ATR Data on Northbound Approach of Belmont Ridge Road

- This indicates the zig-zag pavement markings had a positive effect in terms of speed reduction at the beginning of the zig-zag zone.

- At 250 feet, mean speeds in the after period are all higher by a statistically significant amount than in the before period. This indicates the zig-zag markings had a negative effect in terms of speed reduction.

Table 2 shows the mean speed for each data point over time. Multiple comparison tests for all pair-wise differences between the means were performed for each case, and significant differences at a 95 percent confidence interval are shown in parentheses. For example, at 850 feet, the mean speed in the before case (45.3 mph) is significantly different than 3 (mean speed in the 6-month after case) and 4 (mean speed in the 1-year after case). Detailed descriptive statistics for the northbound approach data on Belmont Ridge Road are summarized in Appendix F.

Table 2. Mean Speed Over Time at ATR Locations on Northbound Approach of Belmont Ridge Road

Period	850 ft	500 ft	250 ft	0 ft
1 (Before)	45.3 (3,4)	45.5 (2,4)	40.4 (2,3,4)	--
2 (After)	45.5 (3,4)	38.0 (1,3,4)	45.3 (1,3,4)	41.3 (3)
3 (6 Months After)	40.4 (1,2,4)	45.5 (2,4)	45.8 (1,2,4)	39.4 (2)
4 (1 Year After)	43.3 (1,2,3)	43.2 (1,2,3)	43.4 (1,2,3)	--

( ) = speed significantly different from period (x) at $\alpha = 0.95$; -- = no data captured.

To assess the impacts of localized changes in traffic flow on data captured with the ATRs, average traffic volume profiles were created for each data collection period. If average daily volumes had uncharacteristic profiles, analyses with respect to the effect of the zig-zag markings on speed reduction would be compromised. Figure 17 shows the average traffic volumes obtained on the northbound approach of Belmont Ridge Road over the duration of the study. Although there were slight differences between each period (most notably the peak afternoon volumes during the 6-month after period), the profiles remain relatively consistent thus assuring the validity of the mean speed profiles.

Mean speed profiles for the medium volume condition on the southbound approach of Belmont Ridge Road are shown in Figure 18 (the high and low volume conditions are shown in Appendix E). Because of poor ATR data quality, data points at 250 feet and 0 feet from the crosswalk are missing for the 1-year after period. The profiles indicate an increase in mean speeds for all before and after data points from 2,000 feet to 500 feet from the crosswalk. This is an intuitive result because of the sharp downhill grade between these points. Upon vehicles entering the zig-zag zone at 500 feet from the crosswalk, there is little difference between mean vehicle speeds during each period. Past this 500-foot distance, key trends include:

- At 250 feet, mean speeds decreased for each period with the greatest decrease occurring during the 1-week after period. This indicates the zig-zag markings had a positive effect in terms of speed reduction.

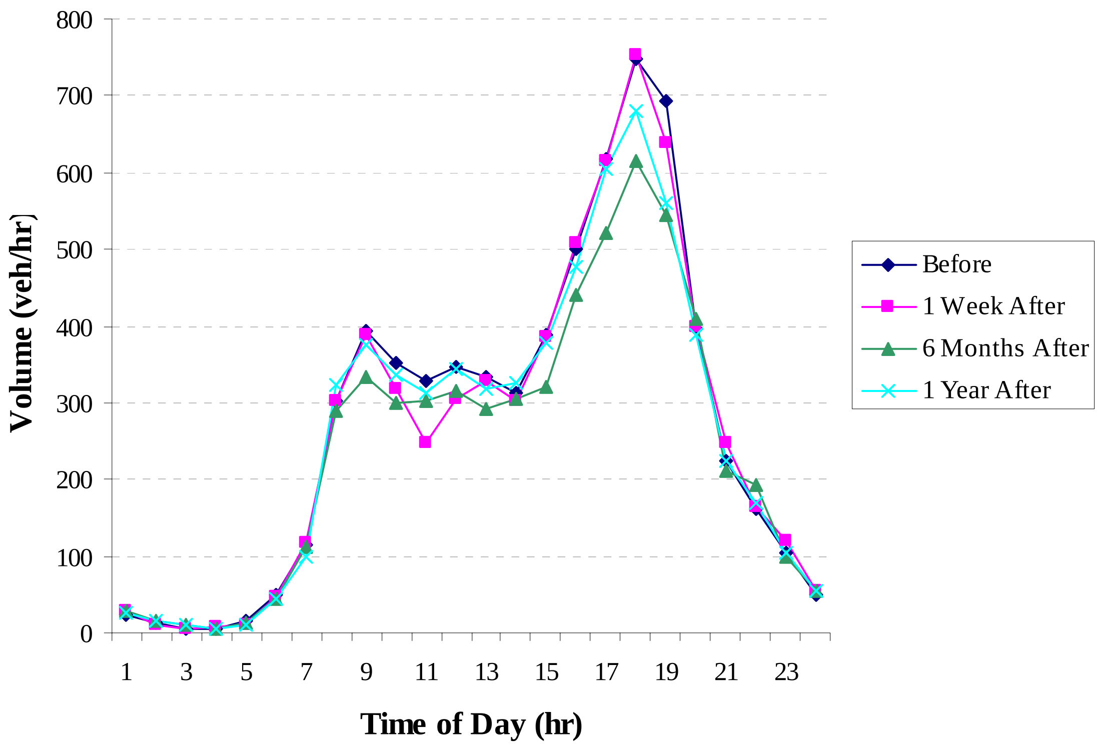

Figure 17. Average Before and After Northbound Traffic Volume Profiles on Belmont Ridge Road

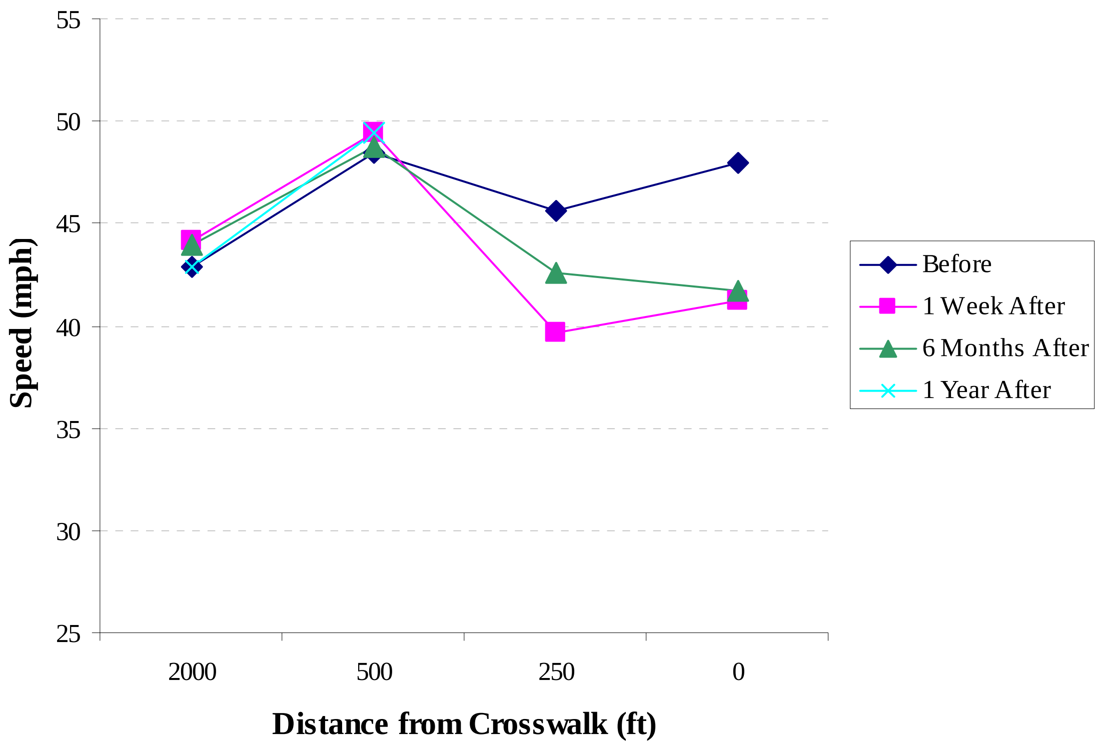

Figure 18. Mean Speed Profiles from ATR Data on Southbound Approach of Belmont Ridge Road

- At the crosswalk (0 feet), mean speeds in the 1-week after and 6-month after periods remained lower than in the before period by a statistically significant amount. The small difference between the 1-week and 6-month after speeds (41.2 mph and 41.7 mph, respectively) suggests that the zig-zag markings maintained the positive effect on speed reduction over a sustained period.

Table 3 summarizes the mean speeds for each data point over time and associated statistically significant differences. Detailed descriptive statistics for these data are provided in Appendix F.

Figure 19 shows the average traffic volumes obtained on the southbound approach of Belmont Ridge Road over the duration of the study. Again, the profiles exhibited consistency, thus providing more assurance of the validity of the speed profiles.

Table 3. Mean Speed Over Time at ATR Locations on Southbound Approach of Belmont Ridge Road

Scenario	2,000 ft	500 ft	250 ft	0 ft
1 (Before)	42.9 (2,3)	48.5 (2,4)	45.6 (2,3)	48.0 (2,3)
2 (1 Week After)	44.2 (1,4)	49.4 (1,3)	39.7 (1,3)	41.2 (1,3)
3 (6 Months After)	44.0 (1,4)	48.7 (2,4)	42.6 (1,2)	41.7 (1,2)
4 (1 Year After)	42.9 (2,3)	49.4 (1,3)	---	--

( ) = speed significantly different from period (x) at α = 0.95; -- = no data captured.

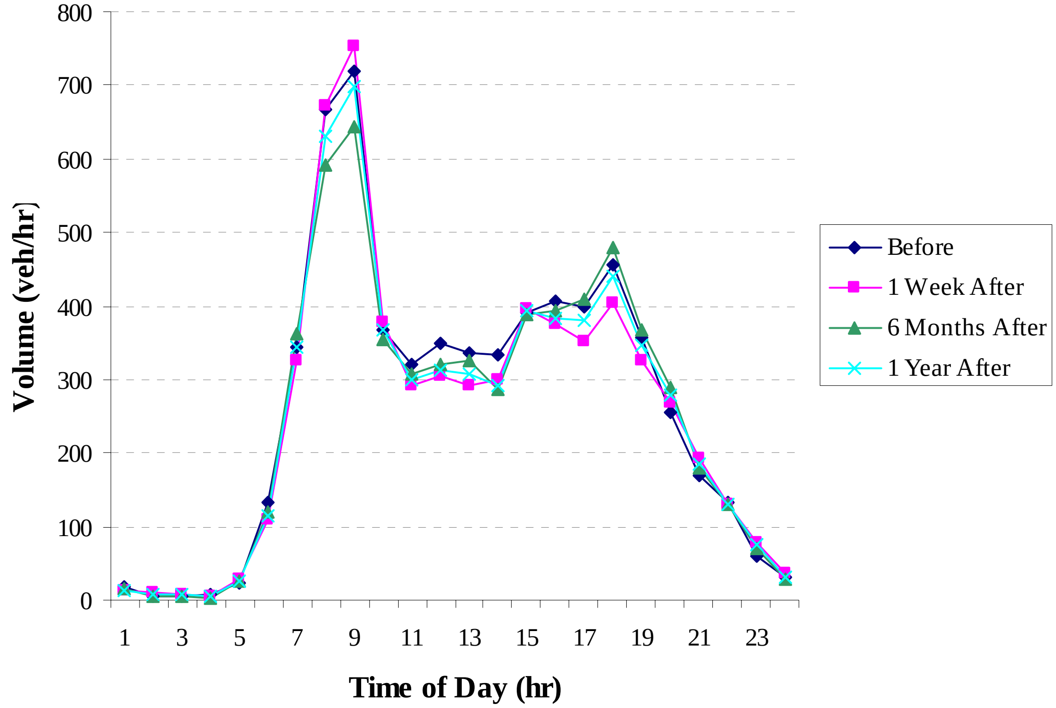

Figure 19. Average Before and After Southbound Traffic Volume Profiles on Belmont Ridge Road

Sterling Boulevard

Figure 20 shows the mean speed profiles for the medium volume condition on the eastbound right lane approach of Sterling Boulevard (the high and low volume conditions are shown in Appendix G). Relevant trends are noted as follows:

- There is a pronounced downward trend in speeds from 2,000 feet to the crosswalk. This may be, in part, attributable to the reduction in speed limit from 40 mph to 35 mph just downstream of the trail crossing.

- At 500 feet, there is a statistically significant mean speed differential between the before data and the 1-week after data (Δ = 3.1 mph). The positive effect on speeds at this distance was maintained throughout the study period (e.g., 6-month and 1-year after mean speeds changed little from the 1-week after mean speeds).

- At 250 feet, the mean speed in the before period (35.3 mph) remained higher than in the after periods in which mean speeds fluctuated from 34.3, 32.6, and 34.1 mph in the 1-week after, 6-month after, and 1-year after periods, respectively.

- At the crosswalk (0 feet), all after mean speeds remained below the before mean speed. Of note, during the 6-month after and 1-year after periods, lower mean speeds from that of the 1-week after period were sustained, suggesting a sustained positive effect of the zig-zag markings and possibly a contradiction of the notion of a novelty effect (e.g., after time, mean speeds rebound to speeds in the before period).

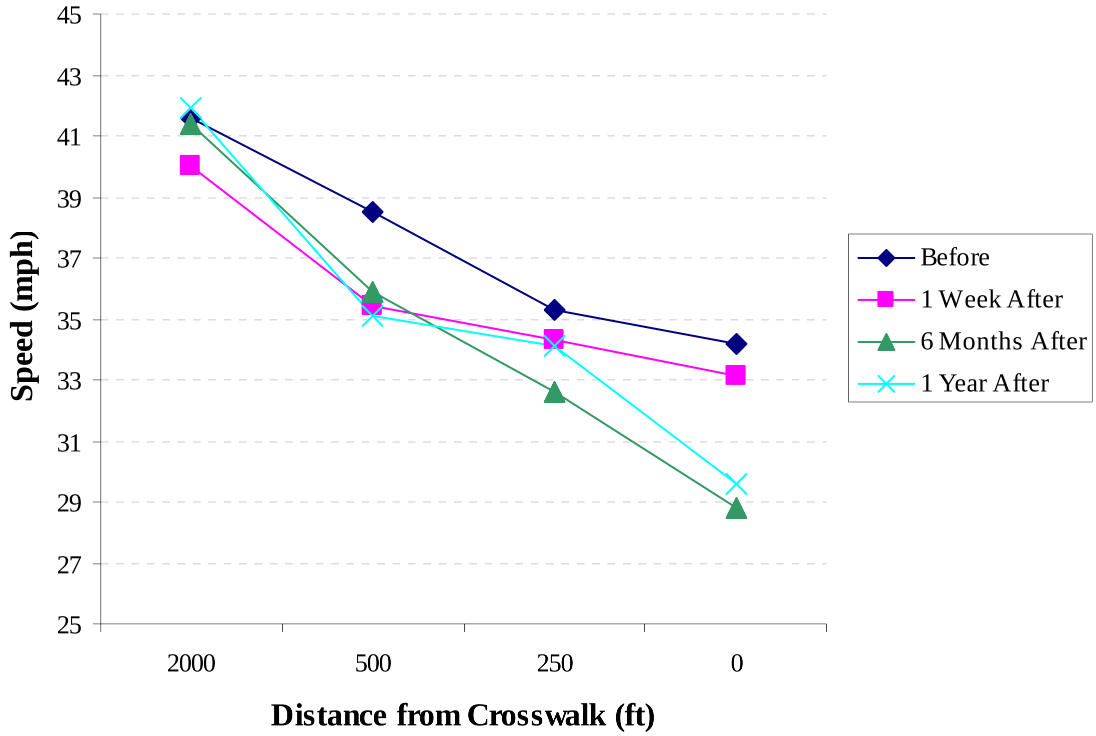

Figure 20. Mean Speed Profiles From ATR Data on Eastbound Right Lane Approach of Sterling Boulevard

Table 4 shows the mean speeds for each data point over time and associated statistically significant differences. Detailed descriptive statistics for these data are summarized in Appendix H.

Speed profiles for the eastbound left lane of Sterling Boulevard are shown in Figure 21. Data points at 2,000 and 500 feet are missing for the 1-year after period because of poor ATR data quality. Noteworthy trends include:

- Mean speeds at 2,000, 500, and 250 feet from the crosswalk were higher in the after periods than the before period. At 250 feet (longitudinal middle of the zig-zag markings), mean speeds rose a statistically significant amount from 35.8 mph in the before period to 38.8 mph in the after period. This indicates that the zig-zag markings had a negative effect on speed reduction on this approach lane. A plausible explanation may be that motorists in the left lane were inclined to drive at a faster rate of speed to get past vehicles traveling at slower speeds in the right lane (see Figure 20).

Table 4. Mean Speed Over Time at ATR Locations on the Eastbound Right Lane Approach of Sterling Boulevard

Scenario	2000 ft	500 ft	250 ft	0 ft
1 (Before)	41.6 (2,3,4)	38.5 (2,3,4)	35.3 (2,3)	34.2 (2,3,4)
2 (1 Week After)	40.0 (1,3,4)	35.4 (1,3)	34.3 (1,3)	33.1 (1,3,4)
3 (6 Months After)	41.4 (1,2,4)	35.9 (1,2,4)	32.6 (1,2)	28.8 (1,2,4)
4 (1 Year After)	41.9 (1,2,3)	35.1 (1,3)	34.1 (1,3)	29.6 (1,2,3)

( ) = speed significantly different from period (x) at α = 0.95.

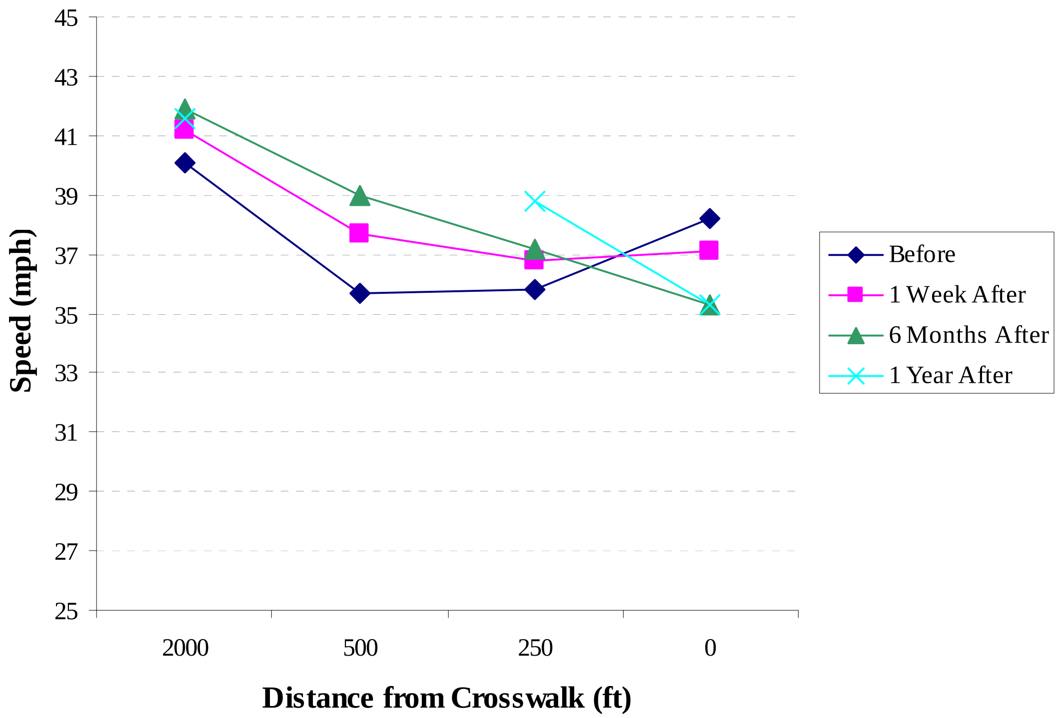

Figure 21. Mean Speed Profiles From ATR Data on Eastbound Left Lane Approach of Sterling Boulevard

- Generally, all after data curves exhibited decreasing trends. However, the before data show a statistically significant spike in mean speed from 250 feet to 0 feet (35.8 to 38.2 mph, respectively). This spike crossed the after data curves, and thus, all after mean speeds were lower at the crosswalk than in the before period, which indicates that the zig-zag lines had a positive effect on speed reduction at the crosswalk.

Table 5 shows the mean speeds for each data point over time and associated statistically significant differences. Detailed descriptive statistics for these data are provided in Appendix H.

Figure 22 shows the average traffic volumes obtained on the eastbound approach of Sterling Boulevard over the duration of the study. Volumes during the 1-year after period were slightly lower than in all other periods, but the profiles remained relatively consistent, thus indicating no consequential localized changes in traffic flow to compromise speed analyses.

Figure 23 shows the mean speed profiles for the right lane on the westbound approach at Sterling Boulevard. Data points at 2,300 feet for the before period and 500 feet for the 1-week after and 6-month after periods are missing because of poor ATR data quality. In a phenomenon

Table 5. Mean Speed Over Time at ATR Locations on Eastbound Left Lane Approach of Sterling Boulevard

Scenario	2,000 ft	500 ft	250 ft	0 ft
1 (Before)	40.1 (2,3,4)	35.7 (2,3)	35.8 (2,3,4)	38.2 (2,3,4)
2 (1 Week After)	41.2 (1,3,4)	37.7 (1,3)	36.8 (1,3,4)	37.1 (1,3,4)
3 (6 Months After)	41.9 (1,2,4)	39.0 (1,2)	37.2 (1,2,4)	35.3 (1,2)
4 (1 Year After)	41.6 (1,2,3)	--	38.8 (1,2,3)	35.3 (1,2)

( ) = speed significantly different from period (x) at α = 0.95; -- = no data captured.

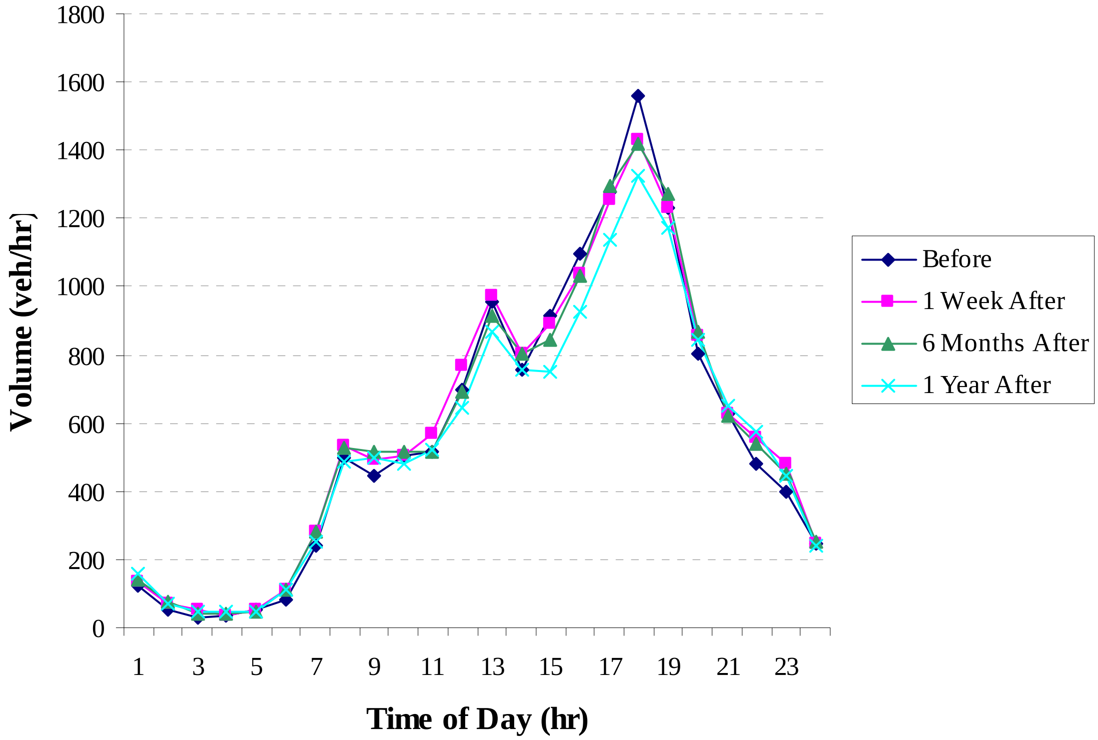

Figure 22. Average Before and After Eastbound Traffic Volume Profiles on Sterling Boulevard

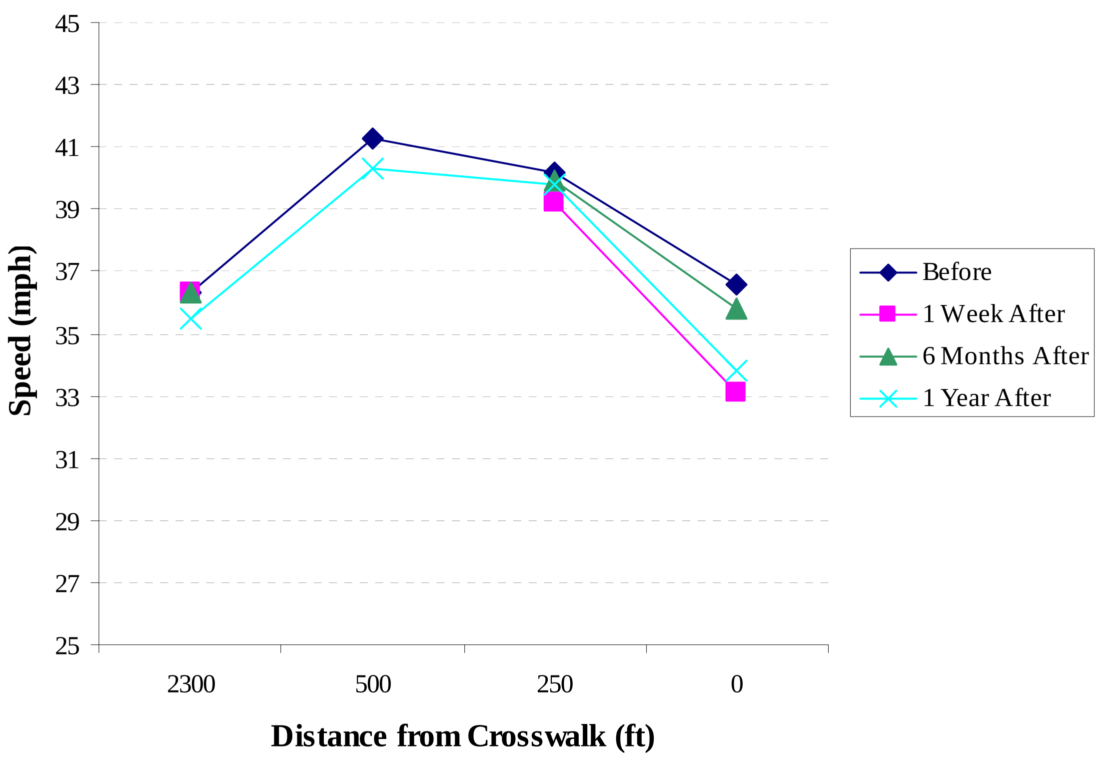

Figure 23. Mean Speed Profiles From ATR Data on Westbound Right Lane Approach of Sterling Boulevard

similar to the data results for the southbound approach at Belmont Ridge Road, mean speeds increased in all periods from 2,300 to 500 feet. One plausible explanation is that vehicles may be accelerating at this point. Additional notable trends include:

- From the beginning of the zig-zag zone to the crosswalk (500 to 0 feet), all mean speed data in the after periods were lower than in the before period. This indicates that the zig-zag lines had a positive effect on speed reduction.

- At the crosswalk, mean speeds fluctuated from 33.1 to 35.8 to 33.8 mph in the 1-week after, 6-month after, and 1-year after periods, respectively. The data suggest that there was a novelty effect at this location because mean speeds returned close to the baseline (before case) in the 6-month after period. However, the mean speed in the 1-year after period decreased to levels close to that in the 1-week after period. This suggests that the zig-zag markings had a sustained positive effect on speed reduction.

Table 6 shows the mean speeds for each data point over time and associated statistically significant differences. Detailed descriptive statistics for these data are shown in Appendix H.

Figure 24 shows the mean speed profiles for Sterling Boulevard's westbound left lane. The data point at 250 feet is missing for the 1-year after period because of poor ATR data quality. The data show a wide distribution of speeds at 2,300 feet from the crosswalk. From 2,300 to 500 feet, there is an increase in speeds in the before and 1-week after periods and a decline in mean speeds in the 6-month and 1-year after periods. Other noteworthy trends include:

- From 500 feet to the crosswalk, all mean speeds in the before period are higher than those in the after period. This indicates that the zig-zag markings had a positive effect on speed reduction.

- At 250 feet, mean speeds dropped from 40.1 mph in the before period to 38.2 mph in the 1-week after period and then increased back up to 39.7 mph in the 6-month after period, thus indicating that there was a novelty affect that expired over time.

- At the crosswalk, all after mean speeds were lower than in the before period by a statistically significant amount. In addition, and in contrast to the observation made previously, mean speeds in the 6-month after and 1-year after periods were lower than the 1-week after mean speed, thus indicating a sustained positive effect on speed reduction close to the crosswalk.

Table 6. Mean Speed Over Time at ATR Locations on Westbound Right Lane Approach of Sterling Boulevard

Scenario	2,300 ft	500 ft	250 ft	0 ft
1 (Before)	36.3 (4)	41.3 (4)	40.2 (2,3,4)	36.6 (2,3,4)
2 (1 Week After)	36.3 (4)	--	39.2 (1,3,4)	33.1 (1,3,4)
3 (6 Months After)	36.3 (4)	--	39.9 (1,2)	35.8 (1,2,4)
4 (1 Year After)	35.5 (1,2,3)	40.3 (1)	39.8 (1,2)	33.8 (1,2,3)

( ) = speed significantly different from period (x) at α = 0.95; -- = no data captured.

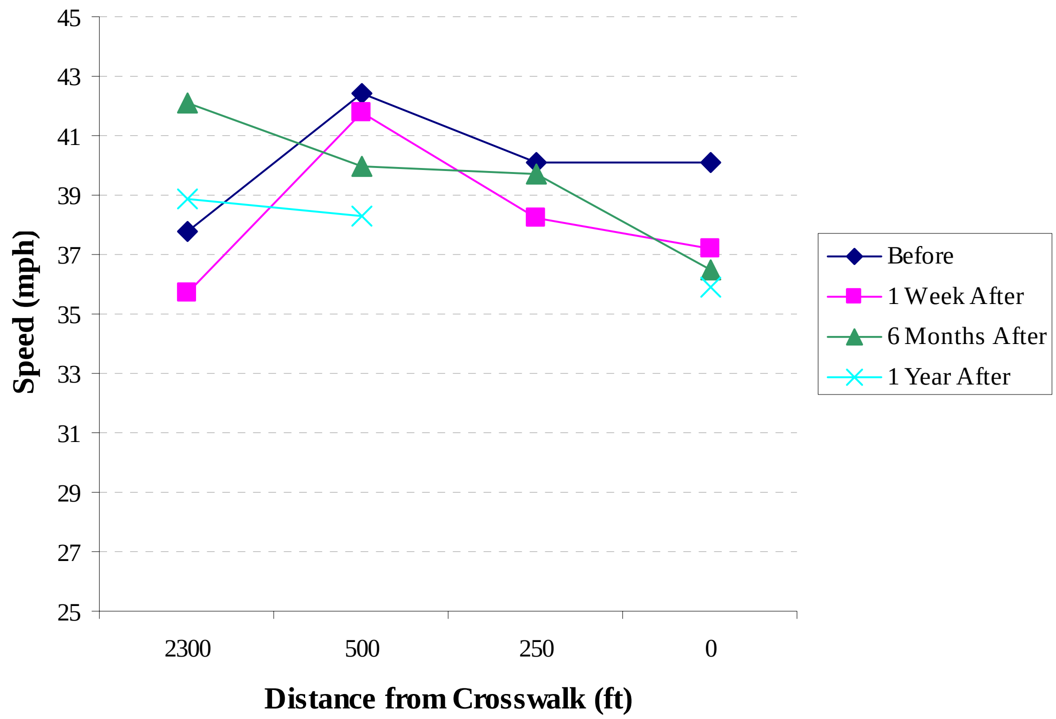

Figure 24. Mean Speed Profiles From ATR Data on Westbound Left Lane Approach of Sterling Boulevard

Table 7 shows the mean speeds for each data point over time and associated statistically significant differences. Detailed descriptive statistics for these data are summarized in Appendix H.

Figure 25 shows the average traffic volumes obtained on the westbound approach of Sterling Boulevard. The profiles remained relatively consistent over the study period, which helped to validate the integrity of the mean speed profiles.

Table 7. Mean Speed Over Time at ATR Locations on Westbound Left Lane Approach of Sterling Boulevard

Scenario	2,300 ft	500 ft	250 ft	0 ft
1 (Before)	37.8 (2,3,4)	42.4 (2,3,4)	40.1 (2,3)	40.1 (2,3,4)
2 (1 Week After)	35.7 (1,3,4)	41.8 (1,3,4)	38.2 (1,3)	37.2 (1,3,4)
3 (6 Months After)	42.1 (1,2,4)	40 (1,2,4)	39.7 (1,2)	36.5 (1,2,4)
4 (1 Year After)	38.9 (1,2,3)	38.3 (1,2,3)	--	35.9 (1,2,3)

( ) = speed significantly different from period (x) at α = 0.95; -- = no data captured.

Control Sites

As discussed previously, the primary reason for collecting control site data was to identify any possible changes in the transportation system that would affect vehicle speeds such as construction detours or other events that would increase or decrease system-wide travel patterns. Unfortunately, mean speed profiles could not be created for Sunrise Valley Drive because of too many missing data points because of poor ATR data quality. However, enough good data were available to create speed profiles at Hirst Road, which are shown in Figure 26.

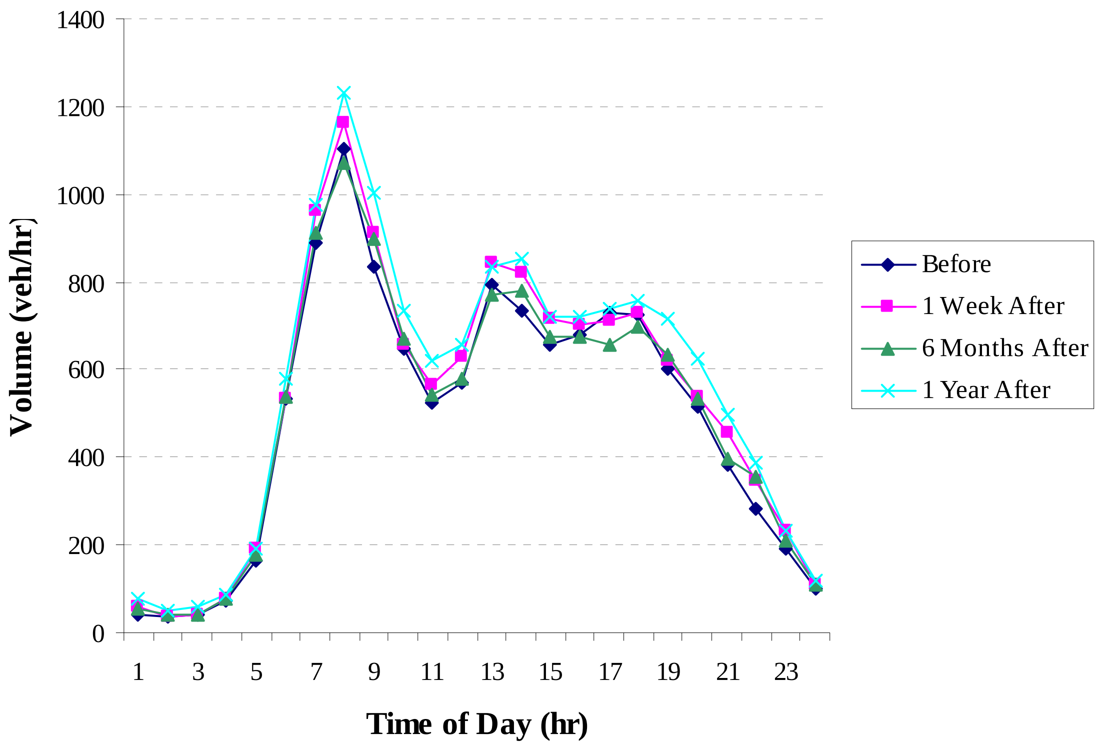

Figure 25. Average Before and After Westbound Traffic Volume Profiles on Sterling Boulevard

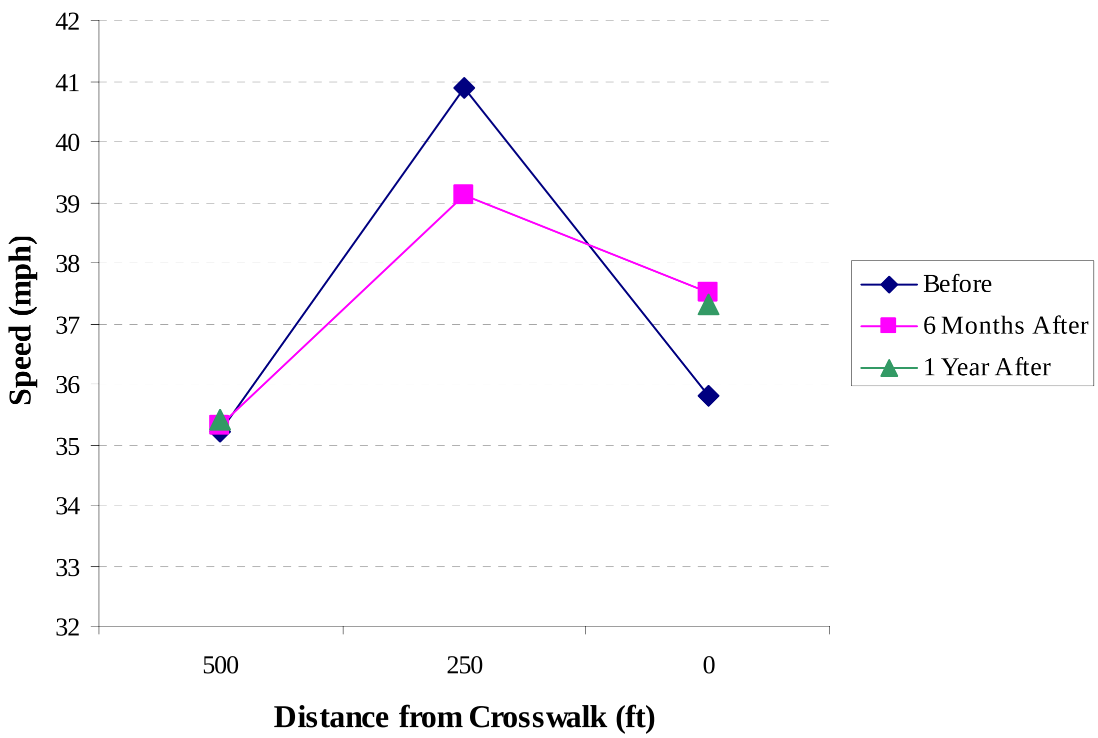

Figure 26. Mean Speed Profiles From ATR Data on Eastbound Approach of Hirst Road

One-year after data are missing at 250 feet because of poor ATR data quality. Noteworthy trends include:

- Mean speeds increased during the before and 6-month after period from 500 feet to 250 feet in advance of the crosswalk.
- At 250 feet, mean speed in the before period was higher than the 6-month after mean speed (40.9 mph compared to 39.1 mph, respectively).
- From 250 feet to the crosswalk, mean speeds decreased by a statistically significant amount for the before and 6-month after periods.
- At the crosswalk, mean speeds in the 6-month and 1-year after periods were higher than in the before period by a statistically significant amount.

Although these data indicate a possible change in system-wide travel patterns, the trend from the before to the after periods is negative at the crosswalk (mean speeds increased). Had the trends been positive (mean speeds decreased), there would be concern that system-wide changes may have influenced the results obtained at Belmont Ridge Road and Sterling Boulevard.

Table 8 provides a summary of the mean speeds for each data point over time and associated statistically significant differences. Detailed descriptive statistics for these data are shown in Table 9.

Table 8. Mean Speed Over Time at ATR Locations on the Eastbound Approach of Hirst Road

Scenario	500 ft	250 ft	0 ft
1 (Before)	35.2	40.9 (2)	35.8 (2,3)
2 (6 Months After)	35.3	39.1 (1)	37.5 (1)
3 (1 Year After)	35.4	--	37.3 (1)

( ) = speed significantly different from period (x) at $\alpha = 0.95$; -- = no data captured.

Table 9. Descriptive Statistics for Speed Data Collected with ATRs on Hirst Road

Scenario	Distance from Crosswalk (ft)	N	Mean (mph)	Standard Deviation (mph)	95% Confidence Interval (mph)	
					Lower Bound	Upper Bound
1 (Before)	500	5179	35.2	6.4	35.0	35.4
	250	5123	40.9	8.4	40.7	41.2
	0	1154	35.8	9.6	35.3	36.2
2 (6 Months After)	500	4570	35.3	6.4	35.1	35.5
	250	4290	39.1	7.8	38.9	39.3
	0	4344	37.5	8.2	37.3	37.8
3 (1Year After)	500	4334	35.4	8.8	35.1	35.6
	250	-	-	-	-	-
	0	5169	37.3	8.2	37.0	37.5

ADT profiles were created for the test sites to identify localized changes in travel patterns that may have impacted speeds. The same procedure was conducted for the control sites. The profiles for Hirst Road and Sunrise Valley Drive are shown in Figures 27 and 28, respectively. The volume scale on the Y-axis is much smaller for Hirst Road, and, therefore, the profiles appear more irregular. However, the peak and off-peak trends are generally consistent. Although mean speed profiles were not constructed for Sunrise Valley Drive because of missing data points, average traffic profiles were constructed to confirm further the consistency of system-wide travel patterns over the duration of the study.

Speeds Obtained with LIDAR Gun

As previously discussed, individual vehicle speeds were obtained by an observer using a LIDAR gun as vehicles progressed toward the crosswalks at Belmont Ridge Road and Sterling Boulevard. Speed data were recorded as a text file and exported to an Excel spreadsheet. Figure 29 shows an example of individual data points (speed and range) for all vehicles tracked during the 1-week after case on the northbound approach at Belmont Ridge Road. The next step was to extract individual vehicles from the output file. Table 10 shows an example of a reconfigured output file for three vehicles.

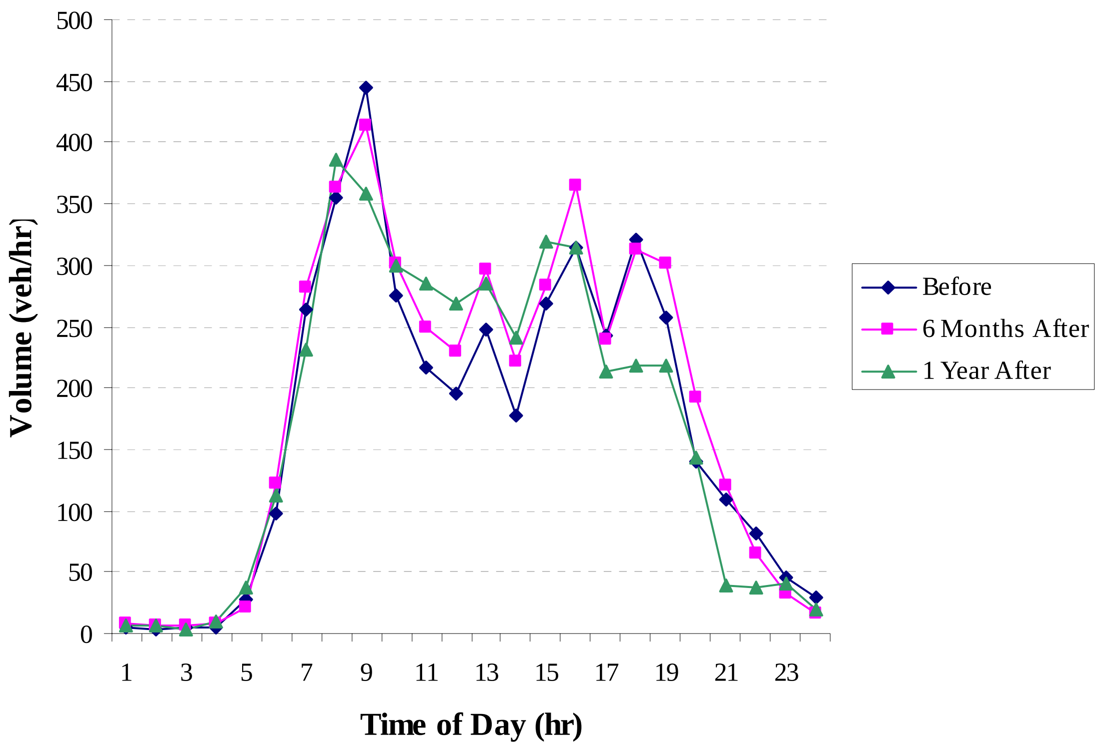

Figure 27. Average Before and After Eastbound Traffic Volume Profiles on Hirst Road

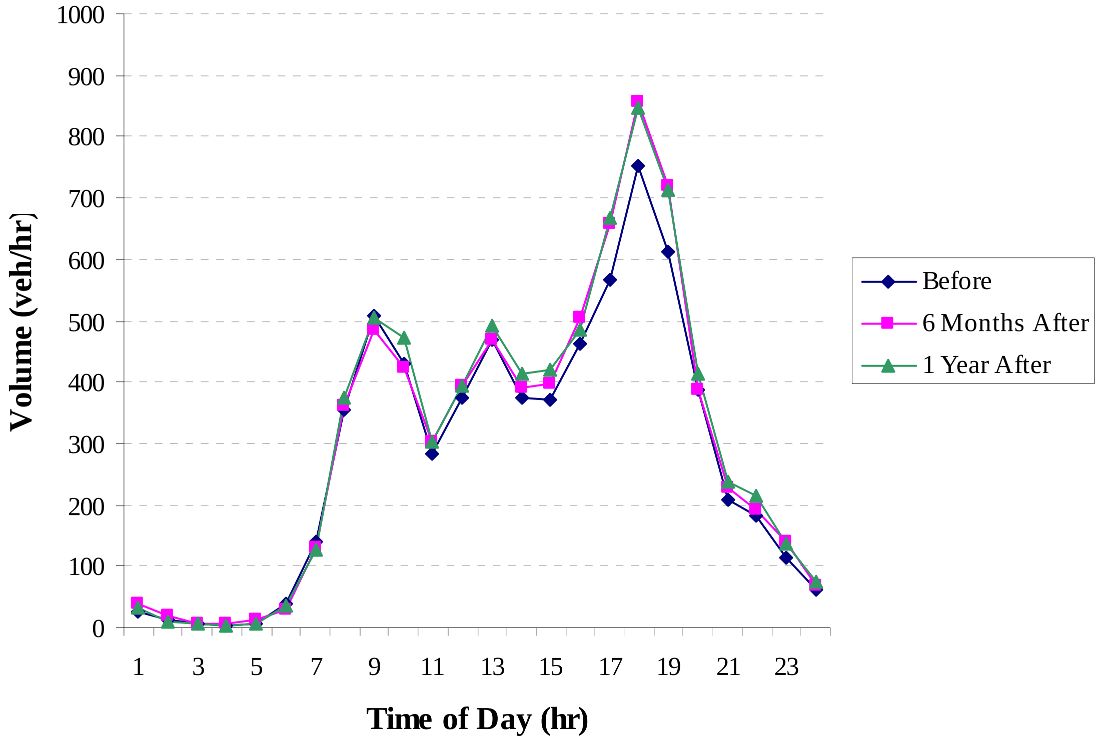

Figure 28. Average Before and After Eastbound Traffic Volume Profiles on Sunrise Valley Drive

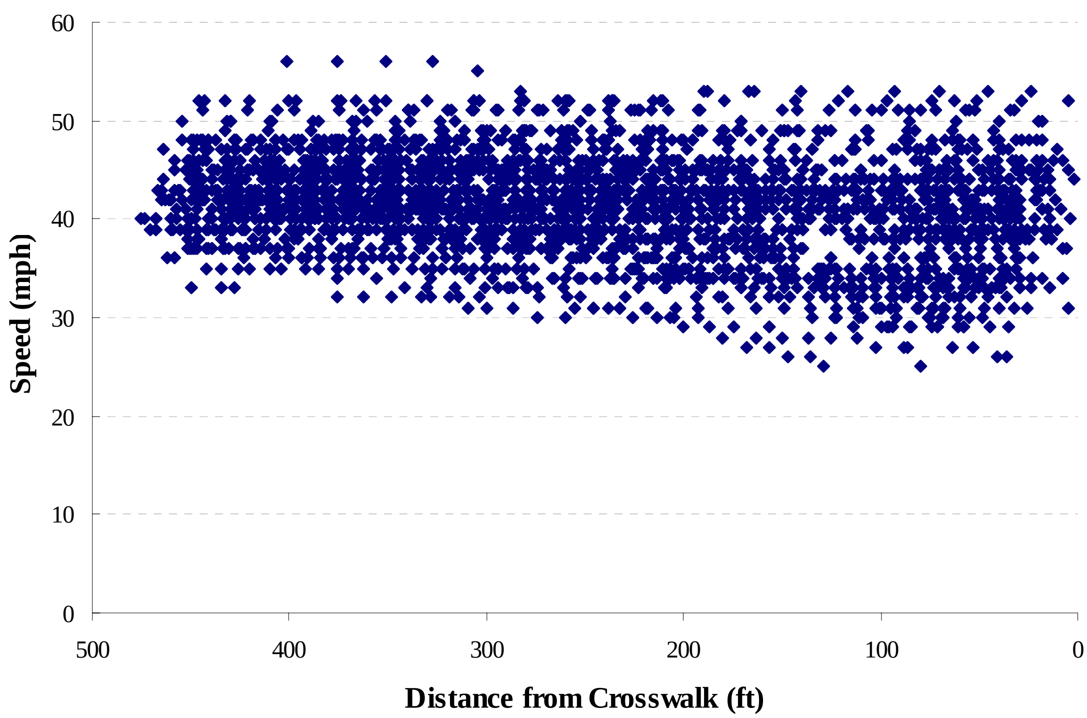

Figure 29. Individual Speed vs. Range Data Points

Table 10. Example of LIDAR Gun Speed and Range Output File

Vehicle 1		Vehicle 2		Vehicle 3	
Speed (mph)	Distance (ft)[a]	Speed (mph)	Distance (ft)[a]	Speed (mph)	Distance (ft)[a]
39	460	43	455	40	468
39	441	43	436	40	450
39	423	43	417	40	433
40	405	43	399	40	417
40	387	43	379	39	398
40	370	43	359	39	382
40	352	43	340	38	365
39	335	43	322	38	349
39	319	42	303	37	332
38	303	42	284	37	316
37	287	42	266	36	300
36	254	42	248	36	284
36	239	42	229	36	268
36	223	41	211	36	252
35	207	41	192	36	236
35	192	41	179	36	220
35	177	41	163	36	204
34	162	40	102	36	188
34	147	40	84	35	126
34	132	40	67	35	125
33	103	40	49	35	96
33	88	40	31	34	80
33	73	40	14	34	65
33	58			34	50
				34	34

[a] Distances were measured from an observer upstream of the crosswalk.

The raw data obtained in the field were then reduced to provide mean vehicle speeds in range bins. For the northbound approach on Belmont Ridge Road, the range bins were 0-100, 101-200, 201-300, 301-400, and 401-500 feet from the crosswalk. Because the observer’s view of the crosswalk was limited by the horizontal curve on this approach, vehicles were tracked after they entered the zig-zag zone. For the southbound approach, the observer was located 1,200 feet upstream of the crosswalk and thus was able to capture vehicle speeds prior to vehicles entering the zig-zag zone. The range bins on this approach were 0-200, 201-400, 401-600, 601-800, and 801-1000 feet from the crosswalk.

On the eastbound approach at Sterling Boulevard, the locations for which the observer could obtain data were limited because of roadway geometry; thus speeds could be tracked only halfway into the zig-zag zone. The range bins on this approach were 0-100, 101-200, and 201-300 feet from the crosswalk. On the westbound approach, line-of-sight limitations prevented data from being captured prior to vehicles entering the zig-zag zone. Therefore, the range bins on this approach were 0-100, 101-200, 201-300, 301-400, and 401-500 feet from the crosswalk.

To allow for cleaner data representation and analysis, individual speeds were averaged within each range bin. Table 11 is an example of how this was accomplished for the same vehicles shown in Table 10. Mean vehicle speeds were then averaged for all samples. For

Table 11. Mean Vehicle Speeds (mph) per 100-ft Segment NB on Belmont Ridge Road

Distance from Stop Bar (ft)	Vehicle 1[a]	Vehicle 2[a]	Vehicle 3[a]
500-401	39.3	43.0	40.0
400-301	39.3	42.8	38.0
300-201	36.0	41.8	36.0
200-101	34.2	40.8	35.3
100-0	33.0	40.0	34.2

[a] The vehicles are that same as those in Table 10.

example, the mean speed of all three vehicles shown in Table 11 500-401 feet from the crosswalk would be:

$$\frac{39.3+43.0+40.0}{3}=40.8 \text{ mph}$$

Belmont Ridge Road

Speed profiles obtained from the LIDAR data for the northbound approach on Belmont Ridge Road are shown in Figure 30. Notable trends include the following:

- Mean speeds in the before period at each distance were higher than those for each after period and statistically significantly different from the 6-month and 1-year after period at each distance. This indicates that the zig-zag pavement markings had a positive effect on reducing speeds when a trail user was at the crosswalk.

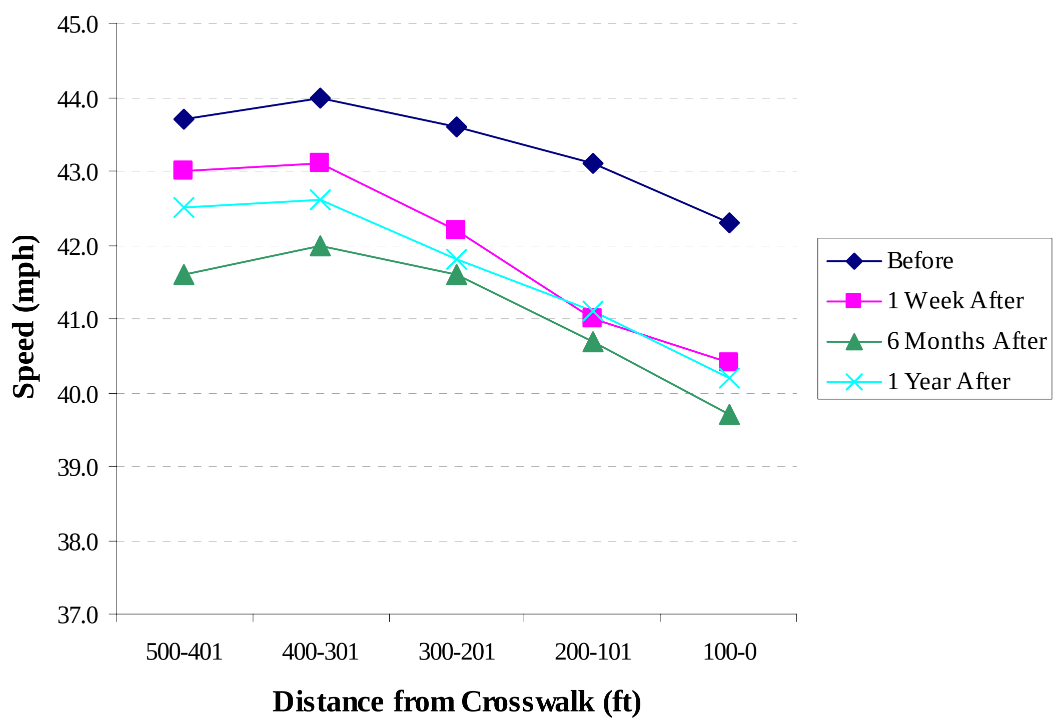

Figure 30. Mean Speed Profiles From LIDAR Data on Northbound Approach of Belmont Ridge Road

- With the exception of the 1-year after period from 101 through 200 feet in advance of the crosswalk, all 6-month and 1-year after mean speeds were lower than the 1-week after speeds. These differences, however, were not statistically different. Nonetheless, this indicates a sustained positive effect on speed reduction over time.

Table 12 shows mean vehicle speeds over time for each distance bin and associated statistically significant differences. Detailed descriptive statistics for these data are summarized in Appendix I.

On the southbound approach, mean speed profiles are shown in Figure 31. Notable trends include the following:

- Mean speeds of vehicles upon entering the zig-zag zone at 500 feet were higher in the before period than in all after periods and were statistically significantly different from the 6-month and 1-year after period.

- From 400 feet to the crosswalk, all after mean speeds were lower than the before mean speed by a statistically significant amount.

Table 12. Mean Speed Over Time Per Distance Bin on the Northbound Approach of Belmont Ridge Road

Period	500-401 ft	400-301 ft	300-201 ft	200-101 ft	100-0 ft
1 (Before)	43.7 (3,4)	44 (3,4)	43.6 (3,4)	43.1 (3,4)	42.3 (3,4)
2 (1 Week After)	43 (3)	43.1 (1,3)	42.2 (1)	41 (1)	40.4 (1)
3 (6 Months After)	41.6 (1,2)	42 (1,2)	41.6 (1)	40.7 (1)	39.7 (1)
4 (1 Year After)	42.5 (1)	42.6 (1)	41.8 (1)	41.1 (1)	40.2 (1)

( ) = speed significantly different from scenario (x) at α = 0.95.

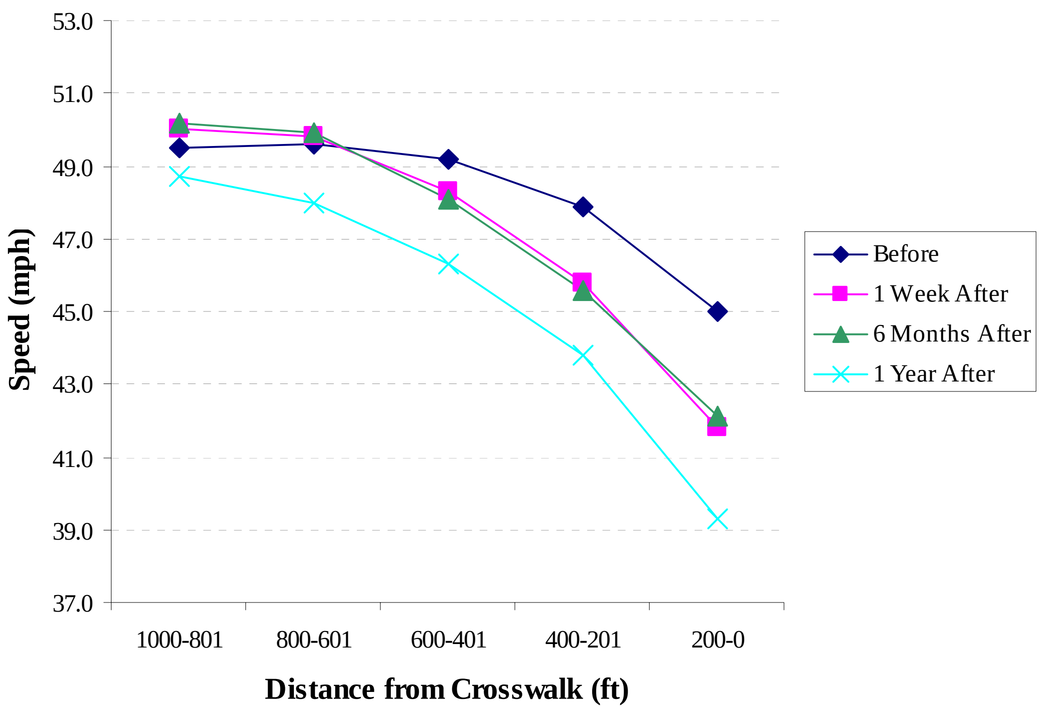

Figure 31. Mean Speed Profiles From LIDAR Data on Southbound Approach of Belmont Ridge Road

- Throughout all data collection periods, there was very little difference in mean speeds at each distance bin for the 1-week after and 6-month after periods. With the exception of the 1000-801 bin, mean speeds during the 1-year after period remained lower by a statistically significant amount than in all other periods. This indicates that the zig-zag markings had a sustained effect on speed reduction over time.

Table 13 shows the mean vehicle speeds over time for each distance bin and associated statistically significant differences. Detailed descriptive statistics for these data are summarized in Appendix I.

Table 13. Mean Speed Over Time Per Distance Bin on the Southbound Approach of Belmont Ridge Road

Period	1000-801 ft	800-601 ft	600-401 ft	400-201 ft	200-0 ft
1 (Before)	49.5	49.6 (4)	49.2 (3,4)	47.9 (2,3,4)	45.0 (2,3,4)
2 (1 Week After)	50.0 (4)	49.8 (4)	48.3 (4)	45.8 (1,4)	41.8 (1,4)
3 (6 Months After)	50.2 (4)	49.9 (4)	48.1 (1,4)	45.6 (1,4)	42.1 (1,4)
4 (1 Year After)	48.7 (2,3)	48 (1,2,3)	46.3 (1,2,3)	43.8 (1,2,3)	39.3 (1,2,3)

( ) = speed significantly different from scenario (x) at α = 0.95.

Sterling Boulevard

Figure 32 shows the mean speed for each distance bin in the right lane of the eastbound approach at Sterling Boulevard. As previously discussed, data were captured after vehicles had traversed halfway into the zig-zag zone. Noteworthy trends include:

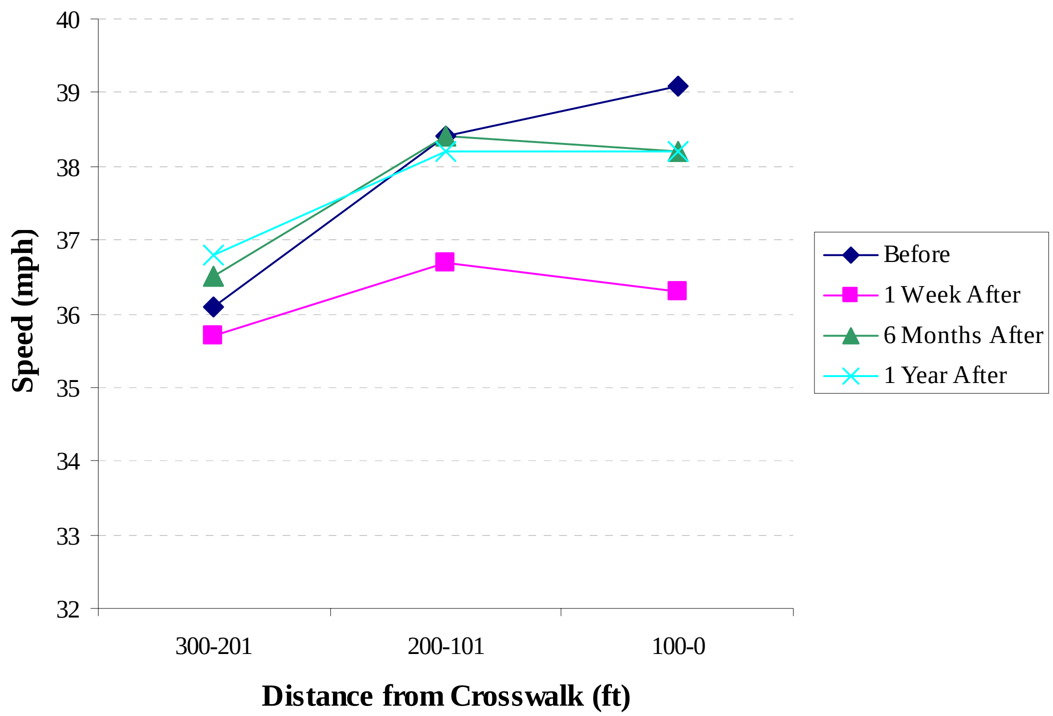

Figure 32. Mean Speed Profiles From LIDAR Data on Eastbound Approach of Sterling Boulevard

- Between 300 and 200 feet from the crosswalk, mean speeds dropped slightly from the before period to the 1-week after period. However, mean speeds in the 6-month and 1-year after period increased from the before period. Speed changes for each case were not statistically significant.

- From 200 feet to the crosswalk, mean speeds were lower in the 1-week after period than in all other periods by a statistically significant amount. This indicates that there was a novelty effect and the zig-zag markings at this location did not have a sustained positive effect on speed reduction. Although Figure 32 shows that mean speeds from 100 feet to the crosswalk during the 6-month and 1-year after period were lower than in the before period, the differences were not statistically significant.

Table 14 shows the mean vehicle speeds over time for each distance bin and associated statistically significant differences. Detailed descriptive statistics for these data are summarized in Appendix J.

Table 14. Mean Speed Over Time Per Distance Bin on the Eastbound Approach of Sterling Boulevard

Period	300-201 ft	200-101 ft	100-0 ft
1 (Before)	36.1	38.4 (2)	39.1 (2)
2 (1 Week After)	35.7 (4)	36.7 (1,3,4)	36.3 (1,3,4)
3 (6 Months After)	36.5	38.4 (2)	38.2 (2)
4 (1 Year After)	36.8 (2)	38.2 (2)	38.2 (2)

( ) = speed significantly different from scenario (x) at $\alpha = 0.95$.

Figure 33 shows the mean speed profiles in the right lane of the westbound approach. Notable trends include:

- As vehicles entered the zig-zag zone at 500 feet, mean speeds for all after periods were lower than in the before period with the 1-week and 1-year after mean speeds being different by a statistically significant amount. This indicates a positive sustained effect on speed reduction as vehicles enter the zig-zag zone.

- From 400 to 100 feet, the mean speeds for the 1-week after period were lower than all other periods by a statistically significant amount. In addition, speed profiles for the before, 1-week after, and 6-month after periods appear to converge, thus indicating a novelty effect.

- From 100 feet to the crosswalk, mean speeds were lower in the 1-week and 1-year after periods than in the before period by a statistically significant amount. Mean vehicle speeds remained relatively constant from 200 feet to the crosswalk in the before period, whereas speeds continued to decline in all after periods. This signifies that in close proximity to the crosswalk, the zig-zag pavement markings had a positive effect on speed reduction.

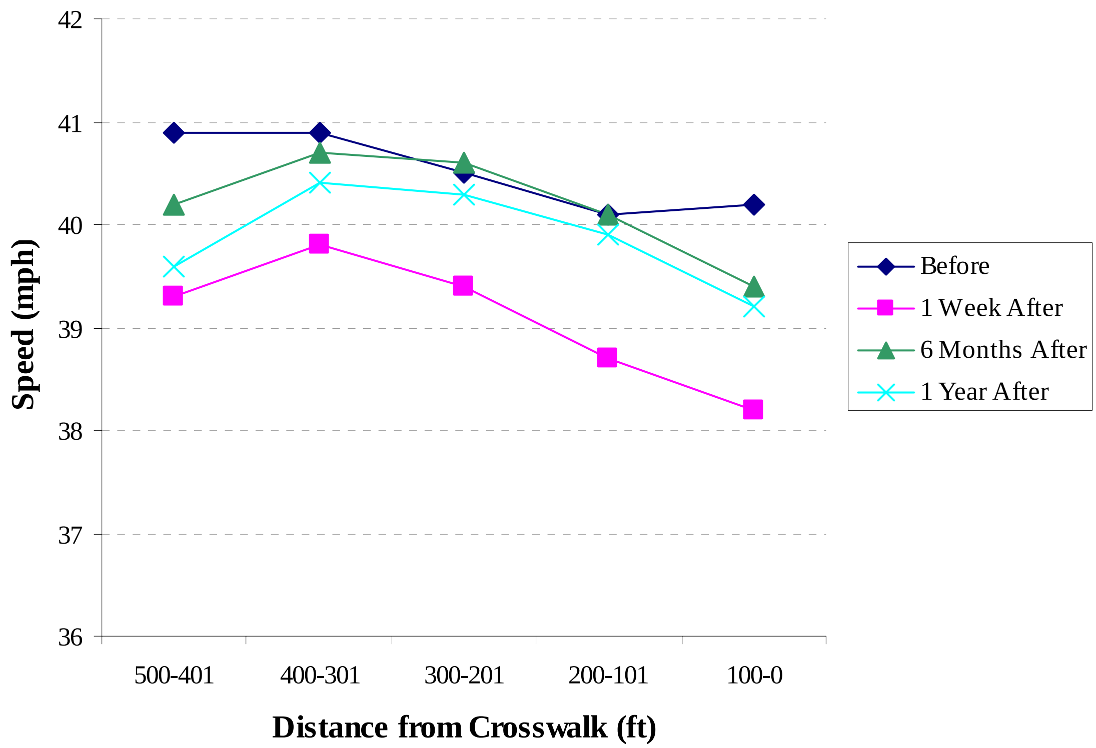

Figure 33. Mean Speed Profiles From LIDAR Data on Westbound Approach of Sterling Boulevard

Table 15 shows the mean vehicle speeds over time for each distance bin and associated statistically significant differences. Detailed descriptive statistics for these data are summarized in Appendix J.

Table 15. Mean Speed Over Time Per Distance Bin on the Westbound Approach of Sterling Boulevard

Period	500-401 ft	400-301 ft	300-201 ft	200-101 ft	100-0 ft
1 (Before)	40.9 (2,4)	40.9 (2)	40.5 (2)	40.1 (2)	40.2 (1,4)
2 (1 Week After)	39.3 (1,3)	39.8 (1,3)	39.4 (1,3,4)	38.7 (1,3,4)	38.2 (1,3,4)
3 (6 Months After)	40.2 (2)	40.7 (2)	40.6 (2)	40.1 (2)	39.4 (2)
4 (1 Year After)	39.6 (1)	40.4	40.3 (2)	39.9 (2)	39.2 (1,2)

( ) = speed significantly different from scenario (x) at α = 0.95.

Before and After Crash Data

Crashes that occurred at or very near the crossing locations were obtained from VDOT and Loudoun County police records for a period of 5 years before and 1 year after installation of the zig-zag markings. On Belmont Ridge Road, 12 crashes were recorded during the before period; 10 were described as rear-end, and 2 as run-off-the-road crashes. In the after period, 3 crashes were recorded, all rear-end crashes. At Sterling Boulevard, 6 crashes were reported during the before period; 5 were rear-end crashes, and 1 was a vehicle-pedestrian crash. During the after period, there was 1 vehicle-pedestrian crash. From the crash descriptions, the cause of the rear-end crashes at both test sites was a trailing vehicle following too closely behind a yielding leading vehicle. Although data were insufficient to perform a comprehensive statistical crash analysis, the data to date indicate that the average yearly crashes have not increased since the zig-zag markings were installed.

Survey Results

This section provides the results of the surveys that were distributed locally in the Loudoun County / Northern Virginia area and at off-site (non-local) locations in the Waynesboro, Staunton, and Charlottesville areas. The purpose of the locally distributed surveys was to obtain opinions on the zig-zag pavement markings from those familiar with the installation. The non-local surveys were performed to obtain reactions from subjects with regard to understanding the purpose or meaning of the markings.

Locally Distributed Surveys

A total of 425 web-based survey responses were obtained from the Loudoun County / Northern Virginia area. The number of submissions by distribution source was as follows:

- Loudoun County Government Office: 84
- Broad Run District Supervisor's Office (Belmont Ridge Road): 224
- Sterling District Supervisor's Office (Sterling Boulevard): 36
- bicycle clubs: 61
- on-site (W&OD Trail): 20.

It is important to note that some submissions were incomplete (i.e., some questions were not answered). For those subjects answering questions specific to operating a motor vehicle and trail use, 93 percent responded that they had driven over the zig-zag pavement markings at Belmont Ridge Road and/or Sterling Boulevard within the past year. Seventy percent of those who had driven on Belmont Ridge Road did so on a frequent basis (at least once a week), whereas 51 percent drove on Sterling Boulevard on a frequent basis. Fifty-five percent of all respondents had bicycled or walked on the W&OD Trail crossing Belmont Ridge Road and/or Sterling Boulevard within the past year (or since the zig-zag markings had been installed). Forty-four percent of those who had used the trail did so on a frequent basis (once a week or more).

As previously mentioned, two subject groups were targeted in the surveys: (1) subjects who had driven over the zig-zag markings, and (2) subjects who had used the W&OD Trail at Belmont Ridge Road and/or Sterling Boulevard. Both groups were asked general questions non-specific to either group. The online versions of the surveys had imbedded skip-logic that directed subjects to appropriate questions based on previously answered questions. For example, if subjects drove over the zig-zag pavement markings on Belmont Ridge Road but not on Sterling Boulevard, they were directed to questions related only to the Belmont Ridge Road markings. Questions 1 through 3 are the general questions that were asked, questions 4 through 8 were directed to motorists only, and questions 9 through 11 were directed to trail users. Survey questions and subject responses follow.

General Questions

1. Have you heard or read news reports about the zig-zag pavement markings?
N (number of responses) = 336

Many news outlets covered the installation of the markings, and 73 percent of the subjects had heard or read news reports. This percentage indicates the public information campaign about the markings reached a majority of the area residents.

2. Why do you think VDOT installed the zig-zag pavement markings?
N = 337

Figure 34 shows the percentages of the types of answers given. Fifty-nine percent of the respondents indicated the correct answer of "increase awareness" of the W&OD Trail. Twenty-three percent gave answers associated with speed reduction. Although speed reduction may be an indicator of increased awareness, the zig-zag markings were not installed specifically to reduce speeds. These results indicate that conveyance of purpose of the markings through public information campaigns could have been improved.

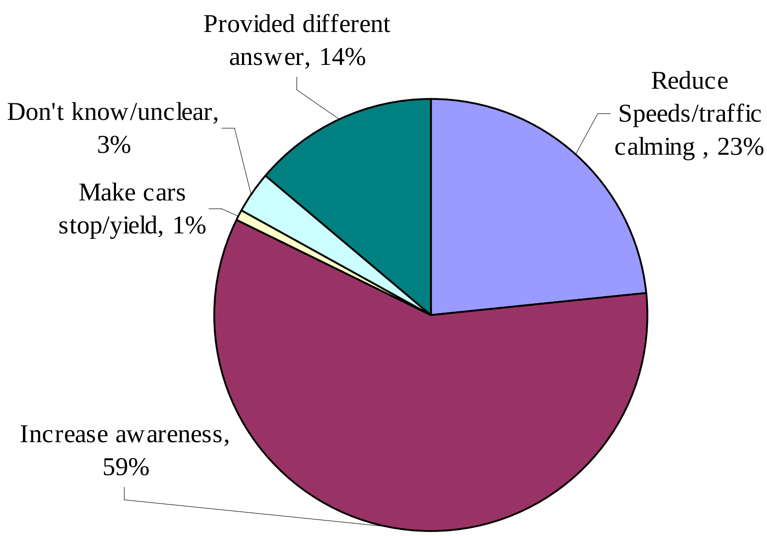

Figure 34. Survey Responses on Why VDOT Installed Zig-zag Markings

3. In your opinion, who has the right-of-way (right to go first) at the trail crossings?
N = 412

Potential for confusion with respect to right-of-way was observed in the field both before and after the zig-zag marking installation. Corroborating these field observations were the opinions on this question where roughly one-third of the responses are in conflict (see Figure 35). Laws regarding right-of-way are written in the *Code of Virginia*. However, some view these laws as unclear, particularly at W&OD Trail crossings where STOP signs are directed toward trail users. This issue is discussed in more detail later.

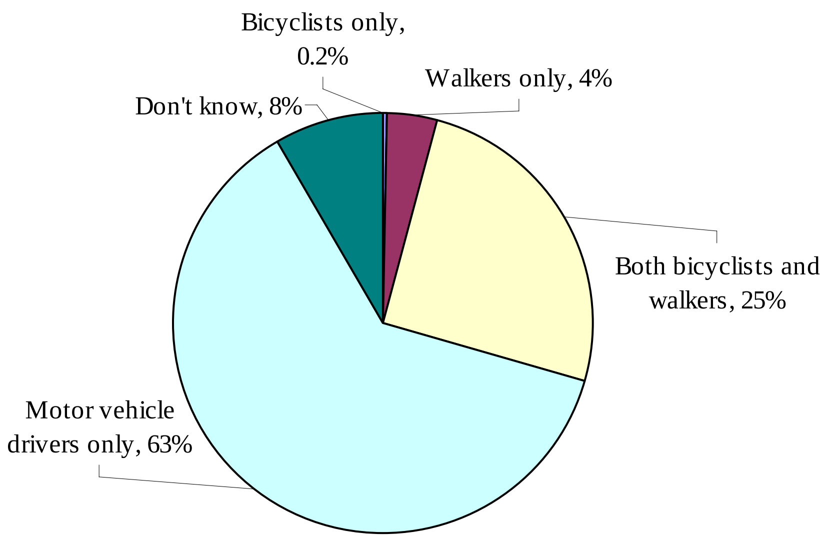

Figure 35. Survey Responses on Who Has Right-of-Way

Questions for Motorists

1. **Have the zig-zag pavement markings altered your driving behavior?**
   N = 309

Seventy-three percent of the respondents indicated that the markings altered their driving behavior: 20 percent responded that the markings altered their driving behavior very much, and 27 percent responded that the markings had no effect on their driving behavior. Subjects were asked to elaborate and the following is a random sampling of responses:

- The W&OD comes up very quickly and the Zig Zag lines reminded me to slow down and be more aware.

- I am more aware that the W & OD Trail road area is coming up, and I do slow down my speed.

- Although I've always been careful at this section of the road, the zig-zag is a good reminder if distracted.

- The zig zags have been there as long as I have been driving that road. I immediately become conscious of the trail when I see them.

- The markings call attention to the crossing and I make sure to be extra careful when approaching.

- Thankfully, the zig-zag strips make other motorists slow down their approach to the intersection. For all involved, I think that this has reduced the number of "panic stops" and also likely rear end collisions caused by this intersection.

- As soon as I hit the zig zags during the day I bring my speed down and look to the left/right of the crosswalk to see if there are pedestrians. If there are, I stop. Before the zig zags, sometimes I would remember and sometimes I wouldn't.

- They are a reminder that the bike path is coming up. Sometimes it is easy to forget. Now I am sure to slow down to see if there is anyone needing to cross.

- I have no idea what I'm supposed to do when I'm going over them. The first few times I slowed. Now I don't change my speed at all.

- I have always been aware of the WO&D crossing and try to keep an eye out for people needing to cross. The markings have not changed my behavior.

2. **Do you agree or disagree that the zig-zag pavement markings increase your driving awareness or attention?**
   N = 308

Figure 36 shows the responses for all motorists who had driven over the markings at Belmont Ridge Road and/or Sterling Boulevard: 61 percent of the respondents agreed, and 27 percent disagreed. This indicates that the majority of motorists think that the purpose of the markings is being served.

Because of the different zig-zag marking designs on Belmont Ridge Road and Sterling Boulevard, the survey results were filtered to target only motor vehicle drivers at each location (i.e., those that had driven over the markings but had not used the trail). Although a direct comparison cannot be made between the Belmont Ridge Road and Sterling Boulevard markings because of the different marking designs and roadway geometries, the survey responses revealed that a higher percentage of motorists on Belmont Ridge Road thought they had a greater awareness (65% agreed or strongly agreed) compared to those on Sterling Boulevard (39% agreed or strongly agreed).

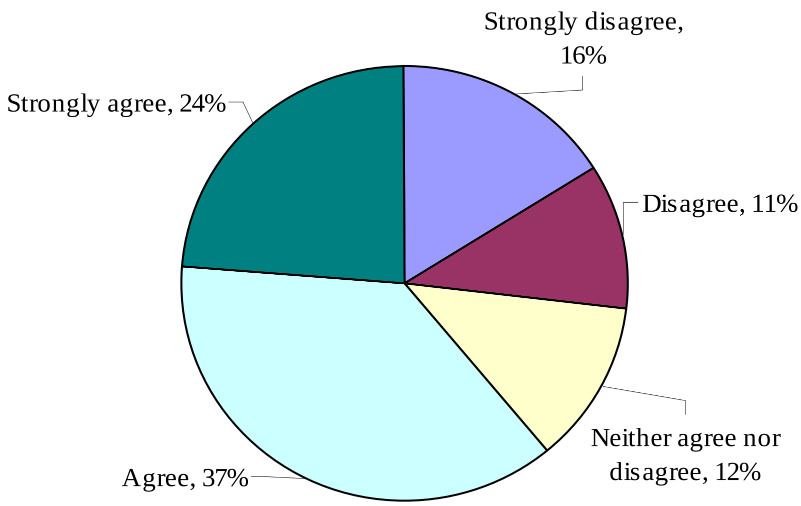

Figure 36. Survey Responses on Increased Driving Awareness or Attention

3. **On a scale of 1-5, please indicate your overall opinion of the zig-zag markings with (1) being a highly unfavorable opinion and (5) being a highly favorable opinion.**
N = 413

Figure 37 shows all responses to this question, including those of trail users. Almost one-half of the respondents (48%) indicated a favorable to highly favorable opinion of the markings, whereas 36 percent indicated an unfavorable to highly unfavorable opinion of the markings.

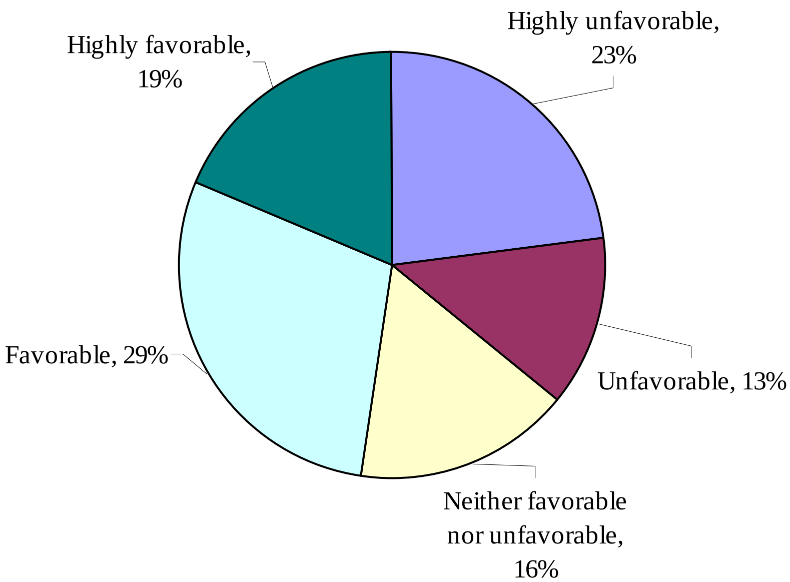

Figure 37. Survey Responses on Overall Opinion of Markings

There was very little middle ground (neither favorable nor unfavorable). Respondents were also asked to indicate why they answered the question as they did. Some of the favorable comments were:

- Anything that draws a motorist attention to pedestrians is a good thing.
- A great, effective tool for traffic management.
- I've seen several near-wrecks at that intersection. The markings drive home the fact that this is a significant yield area.
- More cars seem to hit the brakes upon noticing the marks, making the crossing safer for all.
- Causes very little inconvenience to drivers and potentially saves lives.
- I just like it! It works!
- They are not common, they do catch your attention, therefore making everyone more aware and alert in reference to the crossing ahead.

Some of the unfavorable comments were:

- It’s confusing and distracting. Your attention is spent more on the road, than the approaching intersection.

- I don’t like it, nor do I understand it.

- They create confusion to the driver. Please put appropriate signs explaining their use.

- Drivers are stopping at the zigzags, and waving bicyclists and walkers across. It’s a mess.

- The markings are not known by people and are just a distraction and look silly. A flashing yellow would make more sense.

- They give bicyclists the wrong the impression that they actually have SOME right of way here. They do not.”

- The zigzag lines cause vehicles to abruptly slow down and stop and endangers motorists and people that are using the trail.

A similar filtering procedure to that used for question 5 was performed to identify how different groups responded to this question. For this question, the survey results were filtered to capture (1) Belmont Ridge Road motorists only, (2) Sterling Boulevard motorists only, and (3) trail users. Based on the percentages, trail users were the most receptive to the zig-zag markings, with 54 percent having a favorable or highly favorable opinion of the markings and 30 percent having an unfavorable or highly unfavorable opinion. The favorable opinions for Belmont Ridge Road mirrored those shown for all responses in Figure 37 (48%), but a higher number of respondents indicated an unfavorable opinion (43%); almost a 50/50 split. Although there were much fewer responses from Sterling Boulevard motorists, the results were still telling. Only 32 percent indicated a favorable opinion of the markings, whereas 50 percent responded with an unfavorable opinion. From these data it might be postulated that motorists view the zig-zag marking design at Belmont Ridge Road more favorably than do motorists at Sterling Boulevard and that trail users view the markings more favorably than motorists.

4. **When bicyclists and/or walkers are waiting to cross at the crosswalk, have the zig-zag pavement markings increased, decreased or had no impact on your tendency to yield?**
   N = 305

This question was directed toward motorists only, and 40 percent of the respondents indicated that the markings increase their tendency to yield whereas 60 percent indicated no impact. Filtering for Belmont Ridge Road and Sterling Boulevard revealed the same percentages. As previously discussed, the intention of the markings is to increase motorist awareness, not to slow vehicles or induce yields. The response to this question indicates that the potential exists for a misunderstanding of the intent of the markings. Further, it illustrates the confusion motorists may have with respect to right-of-way laws.

5. **From a motorist perspective, do you think the zig-zag markings increase safety, have no impact on safety or decrease safety for bicyclists and walkers?**
   N = 308

Fifty-six percent of the respondents answered that the zig-zag pavement marking increase safety for bicyclists and walkers: 25 percent and 19 percent indicated no impact and a decrease in safety, respectively. There were substantial differences when filtering for Belmont Ridge Road and Sterling Boulevard: 58 percent of Belmont Ridge Road respondents indicated an increase in trail user safety as opposed to only 36 percent of Sterling Boulevard respondents. These results suggest that from a motorist perspective, the zig-zag pavement markings installed at Belmont Ridge Road had more of an effect on trail user safety than the markings installed at Sterling Boulevard.

Questions for Trail Users

6. **What effect do you think the zig-zag pavement markings have had on the driving behavior of motorists?**
   N = 225

This question was asked to those who had used the W&OD Trail crossings at Belmont Ridge Road and/or Sterling Boulevard. Seventy-one percent of the respondents indicated that the markings had some impact on the driving behavior of motorists, and 29 percent indicated no effect. This suggests that a majority of trail users has noticed a change in driver behavior since the installation of the zig-zag markings. The respondents were also asked to elaborate on how driver behavior changed. The following is a sampling of the responses:

- Drivers rarely stopped before the markings were installed. Since installation, they stop much more often.
- Drivers slow down more, but do not necessarily yield to pedestrians more.
- More cars appear to be slowing at the zig-zag.
- I still see cars being confused as to who has the right of way. I’ve seen dump trucks nearly rear end cars that slow down for crosswalk.
- They don’t know what to do (some motorists stop short and there is a larger likelihood of a chain reaction crash).

10. **Since the zig-zag pavement markings were installed, have you witnessed a tendency for more vehicles to yield to bicyclists and walkers at the crossing than before?**
    N = 219

Fifty-eight percent of the subjects answered that they have witnessed a tendency for more vehicles to yield at the crossings than before the zig-zag markings were installed. As previously mentioned, the intent of the zig-zag markings was not to increase the yielding rate; however, this finding suggests that the majority of trial users has noticed a change in motorist behavior or reaction.

11. **Do you think the zig zag markings increase safety, decrease safety, or have no impact on safety for bicyclists and walkers?**
N = 225

Fifty-eight percent of the respondents indicated an increase in safety, 26 percent indicated no impact, and 16 percent indicated a decrease in safety. This finding suggests that the majority of trial users think safety at the crossings has improved since the zig-zag markings were installed.

Non-Local Surveys

Because of the media coverage on the zig-zag markings in the Northern Virginia area and the large percentage of subjects who had heard or read news reports about the markings, surveys were conducted in different parts of the state (Waynesboro, Staunton, and Charlottesville) to obtain opinions of the markings from an unbiased pool of subjects. Specifically, subjects were shown pictures of the markings at Belmont Ridge Road and Sterling Boulevard without context (e.g., crosswalk markings and signage were not visible) and asked if they knew the purpose of the markings. Once this question was answered, the subjects were shown a picture of the markings with context (e.g., crosswalk markings and signage were visible) and asked again if they knew the purpose of the markings. A total of 150 surveys were administered; 75 showing the Belmont Ridge Road markings and 75 showing the Sterling Boulevard markings

Belmont Ridge Road

Figure 38 is the photograph of the zig-zag markings at Belmont Ridge Road that was first presented to the survey subjects. The subjects were then asked two questions: (1) Have you ever seen this type of marking on a road, and (2) Do you feel you know the purpose of the pavement marking? For question 1, 73 (97%) respondents answered "no." For question 2, 7 (9%) answered "yes." When asked to explain their answer, 4 of the 7 respondents correctly interpreted the purpose of the markings.

Figure 39 depicts the photograph next shown to the subjects next. Only one question was asked: Seeing this larger field of view, do you feel you know the purpose of the markings? Those who responded "yes" were asked to explain their answer. Thirty-three (44%) of the respondents answered that they knew the purpose of the markings and 29 correctly interpreted the purpose of the markings.

Sterling Boulevard

The same procedure for obtaining opinions on the purpose of the Belmont Ridge Road markings was performed using photographs of the Sterling Boulevard markings (i.e., subjects were asked opinions on the purpose of the markings shown without context and with context). Figure 40 is the photograph of the zig-zag markings at Sterling Boulevard presented first. The subjects were asked: (1) Have you ever seen this type of marking on a road, and (2) Do you feel you know the purpose of the pavement marking? For question 1, 75 (100%) of the respondents

Figure 38. First Photograph Shown to Subjects of Markings on Belmont Ridge Road

Figure 39. Second Picture Shown to Subjects of Markings on Belmont Ridge Road

Figure 40. First Photograph Shown to Subjects of Markings on Sterling Boulevard

answered "no." For question 2, 5 (7%) answered "yes" and when asked to explain their answer, 2 of the 5 respondents correctly interpreted the purpose of the markings.

Figure 41 is the photograph shown to the subjects next. When asked if they knew the purpose of the markings upon seeing the image in a larger field of view, 14 (19%) indicated "yes." Of those, 13 correctly interpreted the purpose of the markings.

DISCUSSION

Zig-zag Marking Patterns

Because of the differences in roadway geometry and traffic characteristics, direct comparisons cannot be made on the effectiveness of the different zig-zag marking patterns at Belmont Ridge Road and Sterling Boulevard with respect to speed reduction. However, the survey results do show that after the zig-zag markings were installed, the percentages of motorists on Belmont Ridge Road that indicated greater awareness (65%), had a favorable opinion of the markings (48%), and indicated trail user safety increased (58%) were higher than associated percentages for Sterling Boulevard (39%, 32%, and 36%, respectively). One plausible explanation for this disparity is that the zig-zag markings on Belmont Ridge Road are more distinct because they traverse down the center of the lanes. Another factor that might contribute to the disparity is that Belmont Ridge Road is located in a more rural corridor with fewer signals, and thus trips along this road are typically longer and motorists may be more inclined to notice changes in their driving environment.

Figure 41. Second Photograph Shown to Subjects of Markings on Sterling Boulevard

Review of the *Code of Virginia*

The results of the locally distributed surveys revealed differing opinions about who has the right-of-way at the W&OD Trail intersections. Of those responding, 63 percent thought motor vehicles have the right-of-way; 28 percent thought trail users; and 8 percent did not know. These percentages underscore the level of uncertainty about right-of-way at the trail crossing and prompted a review by the researcher of the *Code of Virginia* language with respect to crosswalks and right-of-way laws. As previously discussed, STOP signs are directed toward trail users at both Belmont Ridge Road and Sterling Boulevard and high-visibility crosswalks are installed at the roadway crossings. In question, however, is whether or not the STOP signs legally apply to W&OD Trail users at the crosswalks.

With regard to pedestrian right-of-way, § 46.2-100 of the *Code* states that a crosswalk is "any portion of a roadway at an intersection or elsewhere distinctly indicated for pedestrian crossing by lines or other markings on the surface" and § 46.2-924(A) specifies that "the driver of any vehicle on a highway shall yield the right-of-way to any pedestrian crossing such highway at any clearly marked crosswalk." The *Code* appears clear that pedestrians have the right-of-way at marked crosswalks, which would obviously include those at Belmont Ridge Road and Sterling Boulevard.

Two provisions in the *Code* refer to pedestrian control on highways: § 46.2-925 stipulates that where pedestrian control signals exhibiting the words, numbers, or symbols meaning "Walk" or "Don't Walk," such signals shall indicate and apply to pedestrians to cross or not to cross a highway. Further, § 46.2-924(B) states: "No pedestrian shall enter or cross an intersection in disregard of approaching traffic." Since the *Code* does not specify that STOP signs control pedestrians, it appears that pedestrians are not bound to obey STOP signs at Belmont Ridge Road and Sterling Boulevard.

The next step in the review of the *Code* was to investigate references to bicyclists on multi-use paths: § 46.2-904 states: "A person riding a bicycle, electric personal assistive mobility device, motorized skateboard or scooter, motor-driven cycle, or an electric power-assisted bicycle on a sidewalk, shared-use path, or across a roadway on a crosswalk, shall have all the rights and duties of a pedestrian under the same circumstances." Based on the *Code* provisions for pedestrians, this language suggests that bicyclists on the W&OD Trail are not legally bound to obey the STOP signs at Belmont Ridge Road and Sterling Boulevard.

Further review of the *Code* with respect to vehicles (including bicycles) entering a public highway revealed the following: § 46.2-821 states:

> Vehicles before entering certain highways shall stop or yield right-of-way. The driver of a vehicle approaching an intersection on a highway controlled by a stop sign shall, immediately before entering such intersection, stop at a clearly marked stop line, or, in the absence of a stop line, stop before entering the crosswalk on the near side of the intersection, or, in the absence of a marked crosswalk, stop at the point nearest the intersecting roadway where the driver has a view of approaching traffic on the intersecting roadway. Before proceeding, he shall yield the right-of-way to the driver of any vehicle approaching on such other highway from either direction.

Based on this language it would seem appropriate to argue that bicyclists must stop at the STOP sign and yield to main-line traffic. However, § 46.2-100 considers bicycles as "vehicles" only "while operated on a highway." Since the W&OD Trail is not a highway, it could be argued that this provision would not apply to bicyclists on the W&OD Trail.

With regard to language in the *Code* regarding vehicles entering a public highway from a road other than a highway, § 46.2-826 states: "The driver of a vehicle entering a public highway or sidewalk from a private road, driveway, alley, or building shall stop immediately before entering such highway or sidewalk and yield the right-of-way to vehicles approaching on such public highway and to pedestrians or vehicles approaching on such public sidewalk." Again in this case, however, bicycles are not considered "vehicles" by § 46.2-100 because "a private road, driveway, alley, or building" does not meet the *Code's d*efinition of a "highway." Therefore, this code provision does not appear to apply to bicyclists on the W&OD Trail.

These intricacies of the Code may not be known to motorists approaching a W&OD Trail crossing. Motorists see STOP signs directed at trail users and may logically conclude that they have the right-of-way. However, this review indicates that the use of STOP signs in this case does not have a strong foundation in the *Code.*

Comprehension of Zig-zag Meaning

The results of the non-local surveys revealed that the zig-zag markings were met with limited understanding, particularly when the zig-zags were shown without context. This is understandable because these types of markings are not common in the United States. When the zig-zag markings were associated with a crosswalk, the level of understanding increased. This finding indicates that zig-zag markings are not initially understood, but an association can be made if they are tied or connected to crossing treatments and/or devices (such as crosswalks and signs).

Section 1A.02 of the MUTCD[12] states that to be effective, a traffic control device should meet five basic requirements. One of those requirements is "convey a clear, simple meaning." It is evident from the results of the non-local surveys that this is not the case for zig-zag pavement markings. Conversely, findings from the locally distributed surveys revealed a much higher level of comprehension: 73 percent of respondents associated the markings with the crosswalks / W&OD Trail. Notwithstanding familiarity with the W&OD Trail, public information via media coverage likely explains this increased comprehension. Nearly three-fourths of respondents had heard or read news reports about the markings, and this is the same percentage that associated the markings with the W&OD Trail crossings, thus underscoring the significance (and importance) of public information and education campaigns.

CONCLUSIONS

- *Zig-zag pavement markings can enhance safety at locations where there is a need to heighten motorist awareness*. Evidence of heightened awareness with this treatment is evidenced by vehicle speed reductions within the zig-zag marking zones. Moreover, locally administered surveys revealed that nearly three-fourths of respondents traversing the treatment areas noted a heightened awareness. In addition, many said the treatments altered their driving behavior and increased their tendency to yield to trail users.

- *The zig-zag pavement markings had a sustained positive effect on speed reduction*. Speed data revealed that, in most cases, 6-month and 1-year after speeds remained at levels close to or below 1-week after speeds.

- *Zig-zag pavement markings are met with limited understanding as to their purpose*. The non-local surveys revealed that motorists did not understand the meaning of the markings when seen without context (i.e., markings associated with crosswalks and signage). When seen with context, correct interpretations of their meaning increased, but not to levels compatible with guidance set forth in the MUTCD. Public information and education campaigns will help to increase understanding of the zig-zag pavement markings further.

- *W&OD Trail users and motorists on Belmont Ridge Road and Sterling Boulevard are confused regarding who has the right-of-way at the crossings.* Although a majority of survey respondents thought that motorists have the right-of-way, a large percentage did not. This confusion has the potential to increase the risk of crashes at all locations where the W&OD Trail intersects a roadway.

RECOMMENDATIONS

1. *VDOT's Northern Region Traffic Engineering Division should lead an effort to recommend to the FHWA that zig-zag pavement markings be included in the MUTCD as a safety countermeasure at mid-block crossings where there is a need for higher awareness*. This study showed that motorist awareness of mid-block crossings increases with these markings without adversely affecting crash rates over the 1-year study period, thus providing a safer environment for pedestrians, bicyclists, and motorists.

2. *If zig-zag pavement marking language is considered for inclusion in the MUTCD, the National Committee on Uniform Traffic Control Devices should either adopt as guidance the zig-zag pavement marking design parameters presented in this research or develop its own guidance based on additional research*. If the guidance from this research is adopted, it is recommended that (1) the longitudinal length of the pavement markings be based on sight distance and posted speed limit; (2) the longitudinal length of one zig-zag be 24 feet; (3) the marking widths and striping widths be 4 feet and 6 inches, respectively, if installed down the center of a lane; and (4) the marking widths and striping widths be 2 feet and 4 inches, respectively, if installed along center and edgelines.

3. *Pending approval from the FHWA to keep the zig-zag pavement markings at Belmont Ridge Road and Sterling Boulevard, Virginia's Northern Region Traffic Engineering Division should continue to re-mark and maintain the markings*. The markings at both locations resulted in positive motorist reactions in terms of speed reduction and did not adversely affect overall safety.

4. *Given FHWA approval to continue to re-mark and maintain the zig-zag pavement markings indefinitely, VDOT's Northern Region Traffic Engineering Division should monitor and collect data on crashes at both locations for a period of 3 years*. Collecting these data will enable staff at VTRC to perform more comprehensive before and after safety analyses.

5. *A review of the Code of Virginia should be undertaken with respect to those sections dealing with trail users on multiuse pathways and their obligation to comply with non-signalized traffic control devices*. The purpose of the review should be to determine if legislative changes could help alleviate the confusion about right-of-way, and if so, to suggest appropriate legislative change proposals. Such a review could be initiated, or led, by VDOT's Traffic Engineering Division with assistance from staff at VTRC. A cursory review of the *Code* language in this study suggested that trail users on multiuse pathways may not be obligated to comply with non-signalized traffic control devices where the trail intersects a roadway. In addition, the research found there is confusion among motorists and trail users about right-of-way laws regarding the W&OD Trail where a STOP sign is directed toward the trail users. This confusion could compromise safety at these and other similar multiuse trail/roadway intersections.

COSTS AND BENEFITS ASSESSMENT

The research found that the zig-zag pavement markings enhanced safety at the Belmont Ridge Road and Sterling Boulevard W&OD crossings by increasing motorist awareness of pedestrians and bicyclists. This was evidenced by motorist speed reductions after the markings were installed and throughout the study period. Motorist inattention and excessive approach speed are often contributing factors in a crash involving a pedestrian or bicyclist. It is logical to assume, therefore, that the zig-zag markings can lead to a reduction in crashes, both between a vehicle and a pedestrian or bicyclist and between vehicles. The following discussion is based on the supposition that the deployment of zig-zag pavement markings will result in crash avoidance.

In an economic analysis, the costs of crashes that are prevented or avoided are assumed to be the economic benefit of the countermeasure. In this case, costs are related to the installation of the zig-zag markings. For this economic analysis, Belmont Ridge Road was chosen because based on the survey results, the zig-zag pavement markings installed there appeared to have greater effectiveness with respect to motorist awareness than those at Sterling Boulevard. Table 16 shows a comparison of the costs for installing the thermoplastic zig-zag markings at Belmont Ridge Road versus the costs for installing two other countermeasures: advance flashing beacon and overhead flashing beacon systems. Initial installation costs include labor, equipment, and traffic control and, where applicable, materials, design, survey, and electrical service. Initial costs and costs over a 5-year period are shown. For the zig-zag markings, it is anticipated that the markings would have to be reapplied within a 2- to 3-year timeframe. Maintenance and utility costs for a flashing beacon system (one beacon for each approach) are estimated to be $1,500 per year ($750 per beacon).[36]

A data-driven benefit analysis comparing each of the three countermeasures cannot be performed because no studies have directly compared them. However, for this assessment, each countermeasure was assumed to have the same effect on crash avoidance. Several studies have estimated crash modification factors (CMFs) for flashing beacons installed in advance of crosswalks, on overhead mast arms at crosswalks, and in advance of intersections. Although the estimated factors vary depending on an assortment of roadway geometric and traffic characteristics, an estimated value of 0.82 was used in this analysis based on an average value from previous research.[36-38] Accordingly, this percentage was used to estimate the impact the zig-zag pavement markings would have on crash avoidance. At Belmont Ridge Road, there were 12 crashes 5 years prior to the installation of the zig-zag markings. Applying the CMF to this

Table 16. Costs Associated with Installation of Countermeasures

Countermeasure	Initial Installation Cost	Total Cost Over 5 Years[a]
Zig-zag Pavement Markings	$2,850[b]	$5,700[e]
Advance Flashing Beacons	$31,000[c]	$38,200[f]
Overhead Flashing Beacons	$96,000[d]	$103,200[f]

[a]Not discounted to present value.
[b]Labor, equipment, maintenance of traffic, and materials (add $2,200 if eradicating lines).
[c]Labor, equipment, maintenance of traffic, and electrical service.
[d]Design, survey, labor, equipment, maintenance of traffic, and electrical service.
[e]Two striping applications.
[f]Includes maintenance and utility costs of $750 per year per beacon.

number, it is estimated that the zig-zag pavement markings would prevent two crashes over a 5-year period.

The VDOT Highway Safety Improvement Program (HSIP)[39] costs for crashes were used to estimate a monetary benefit from crash reductions over a 5-year period for the three countermeasures shown in Table 17. Those costs per crash are:

- fatality: $3,760,000
- incapacitating injury: $188,000
- evident injury: $42,200
- possible injury: $22,900
- property damage only: $6,500.

Table 17 compares the benefit/cost (b/c) ratio of each countermeasure using the costs per crash figures and the installation/maintenance costs shown in Table 17. Each cost per crash type was doubled because it was estimated that two crashes would be avoided for each countermeasure over a 5-year period. A b/c ratio greater than 1.0 is desirable as it shows that the savings resulting from the benefits of a countermeasure exceed its costs. Based on the b/c ratios shown, the benefits of the zig-zag pavement markings far exceed a “do nothing” approach and those of the other countermeasures. For example, if two evident injury crashes were avoided, the monetary benefits associated with the installation of zig-zag pavement markings would be approximately $91,000 compared to approximately $58,000 for advance flashing beacons and a cost (or disbenefit) of approximately $7,000 for overhead flashing beacons.

Table 17. Costs and Benefits Assessment of Countermeasures

Crash Type	Cost per 2 Crashes Avoided (Benefit)	Benefit-Cost Ratio		
		Zig-zag Pavement Markings	Advance Flashing Beacons	Overhead Flashing Beacons
Fatality	7,520,000	1319:1	196:1	72:1
Incapacitating Injury	376,000	66:1	9.8:1	3.6:1
Evident Injury	96,400	17:1	2.5:1	0.9:1
Possible Injury	45,800	8:1	1.2:1	0.4:1
Property Damage Only	13,000	2.3:1	0.3:1	0.1:1

ACKNOWLEDGMENTS

A number of individuals contributed to this research, and the author appreciates their help and support: Gene Arnold, Cathy McGhee, Mike Fontaine, Amy O’Leary, Lewis Woodson, Penny Via, Linda DeGrasse, Griselle Rivera, Linda Evans, Ed Deasy, and Randy Combs from VTRC; Hari Sripathi, Randy Dittberner, Paul McKenzie, Mary Lou Pagano, Larry Camp, Gene Daliege, Jacob Porter, Ron Sutphin, Jim Lilly, Nestor Martinez, and Joe Obis from VDOT; David Pierce from DMV; Bruce Wright (Fairfax Advocates for Better Bicycling), Randy Karn (Reston Bicycle Club), Dale Hunt (Potomac Pedalers Touring Club), and Pat Turner and Maria Nicklin (Bike Loudoun) from the Northern Virginia area bicycle clubs; Judy Galen and Michael Thompson from the Loudoun County Government Office; Jessica Echard from the Broad Run District; Lauren Quezada from the Sterling District; Karl Mohle from the W&OD Railroad

Regional Park; Paul McCray from the Northern Virginia Regional Park Authority; and Scott Wainwright from FHWA.

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APPENDIX A

REQUEST FOR EXPERIMENTATION AND FEDERAL HIGHWAY ADMINISTRATION APPROVAL LETTERS

COMMONWEALTH *of* VIRGINIA

DAVID S. EKERN, P.E.
COMMISSIONER

DEPARTMENT OF TRANSPORTATION
14685 Avion Parkway
Chantilly, VA 20151
(703) 383-VDOT (8368)

May 30, 2008

Mr. Robert Arnold
Director, Office of Transportation Operations
FHWA
1200 New Jersey Avenue, S.W., HOTO-1
Washington, DC 20590

Dear Mr. Arnold:

This is to request permission to experiment with zig-zag pavement markings at three sites in VDOT's Northern Virginia District as described in the *Request for Experimentation-Zig-Zag Pavement Markings* that is attached. The Virginia Transportation Research Council (VTRC), the research division of the Virginia Department of Transportation, is responsible for the study. The researchers listed at the beginning of the request are the principal investigators. The VTRC will provide FHWA's Office of Transportation Operations with semi-annual progress reports and a completed report upon completion of the experiment. This "request for experimentation' is encompassed in a larger VTRC research effort entitled *Selection, Piloting, and Evaluation of Best Practices in Traffic Operations and Safety, Phase 2*, which has been approved for SPR funding by the FHWA Virginia Division Office.

I am not aware that anyone has existing patents or copyrights on zig-zag pavement markings.

I agree to restore the site of the experiment to a condition that complies with the provisions of the MUTCD within three months following the end of the experiment, unless VDOT or some other agency has submitted a request to change the MUTCD to include this application of pavement markings. Then, markings will be permitted to remain in place until an official rulemaking action has occurred. I also agree to terminate the experimentation at any time that FHWA's Office of Transportation Operations or I determine that there are significant safety concerns directly or indirectly attributable to the experimentation.

Thank you for your consideration of this request. If you have any questions regarding the experimentation, please contact either of the principal investigators at the VTRC as follows:

Lance Dougald, 434-293-1952, Lance.Dougald@VDOT.Virginia.gov
Gene Arnold, 434-293-1931, Gene.Arnold@VDOT.Virginia.gov

Sincerely yours,

Hari Sripathi

Hari K. Sripathi, P. E.
Regional Traffic Engineer

cc: Lance Dougald; Gene Arnold

VirginiaDot.org
WE KEEP VIRGINIA MOVING

U.S. Department of Transportation

Federal Highway Administration

1200 New Jersey Avenue, SE.
Washington, DC 20590

September 9, 2008

In Reply Refer To: HOTO-1

Hari K. Sripathi, P.E.
Regional Traffic Engineer
Virginia Department of Transportation
14685 Avion Parkway
Chantilly, VA 20151

Dear Mr. Sripathi:

Thank you for your May 30 letter requesting approval to experiment with zig-zag pavement markings for additional warning of mid-block crosswalks at two shared-use path crossing locations in the Virginia Department of Transportation's (VDOT) Northern Virginia District. The proposed white zig-zag markings are similar to those currently used in the United Kingdom.

Following our initial review of your original request, comments about the proposed evaluation plan were transmitted to Mr. Lance Dougald of the Virginia Transportation Research Center, the agency that will perform the evaluation for VDOT. After discussing the issues with you, Mr. Dougald submitted a revised experimentation and evaluation plan on August 29. We have reviewed that resubmitted proposal and have found that it addresses our concerns. Therefore, your revised request to experiment is approved for a period not to exceed 2 years from the date of this letter.

For future reference purposes, we have assigned the following official experimentation request number and title to your request: "3-224(E)—Zig-Zag Markings for Crosswalk Warning - Virginia DOT." Please refer to this number in future correspondence.

Thank you for your interest in improving traffic safety through the use of innovative traffic control devices. We look forward to receiving your evaluation reports. If we can be of further assistance on this matter, please contact Mr. Scott Wainwright at **scott.wainwright@dot.gov** or by telephone at 202-366-0857.

Sincerely yours,

Robert Arnold
Director, Office of Transportation
Operations

APPENDIX B

BELMONT RIDGE ROAD ADVANCE WARNING SIGNS AND W&OD TRAIL PAVEMENT MARKINGS AND SIGNAGE

Figure B-1. Southbound Advance Warning Sign

Figure B-2. W&OD Trail Signage and Pavement Markings

APPENDIX C

STERLING BOULEVARD ADVANCE WARNING SIGNS AND W&OD TRAIL PAVEMENT MARKINGS AND SIGNAGE

Figure C-1. Eastbound Advance Warning Sign

Figure C-2. W&OD Trail Signage and Pavement Markings

APPENDIX D

ZIG-ZAG MARKING LAYOUT AND INSTALLATION

Figure D-1. Marking Layout on Northbound Approach of Belmont Ridge Road

Figure D-2. Marking Painting on Northbound Approach of Belmont Ridge Road

Figure D-3. Eradication of Skip-Lines on Sterling Boulevard


Figure D-4. Marking Layout on Eastbound Approach of Sterling Boulevard

Figure D-5. Marking Painting on Eastbound Approach of Sterling Boulevard

Figure D-6. Marking Painting on Westbound Approach of Sterling Boulevard

APPENDIX E

BELMONT RIDGE ROAD NORTHBOUND AND SOUTHBOUND HIGH AND LOW VOLUME SPEED PROFILES FROM ATR DATA

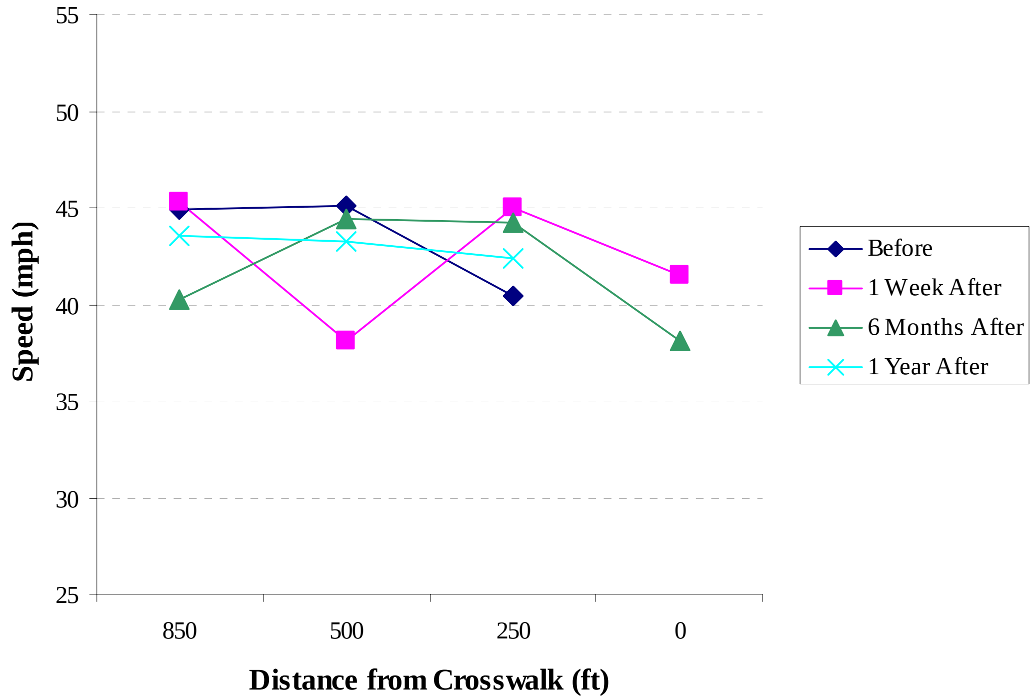

Figure E-1. Northbound High Volume Speed Profiles

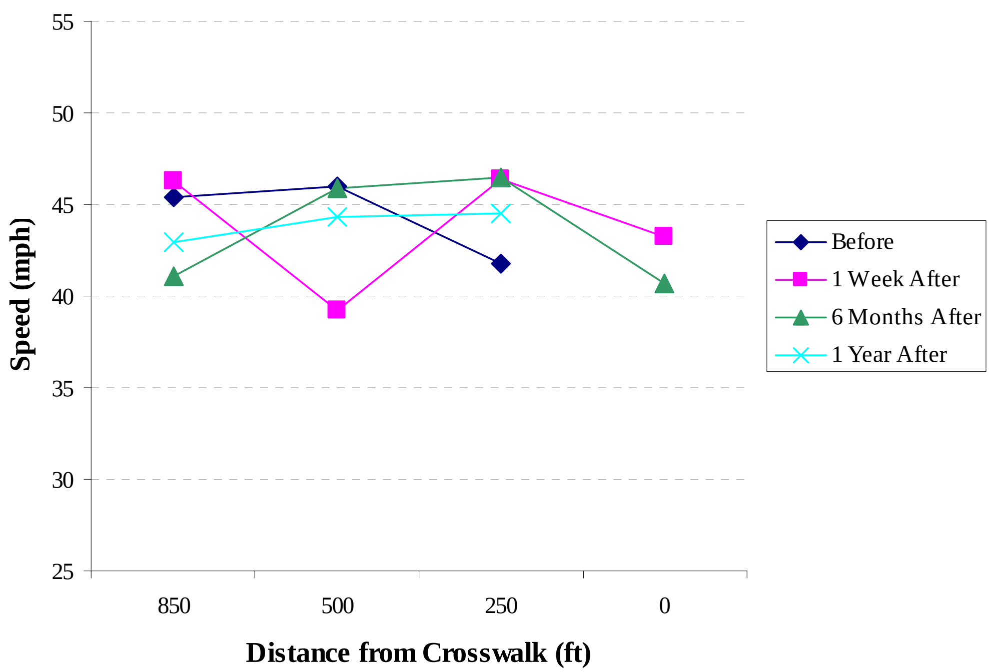

Figure E-2. Northbound Low Volume Speed Profiles

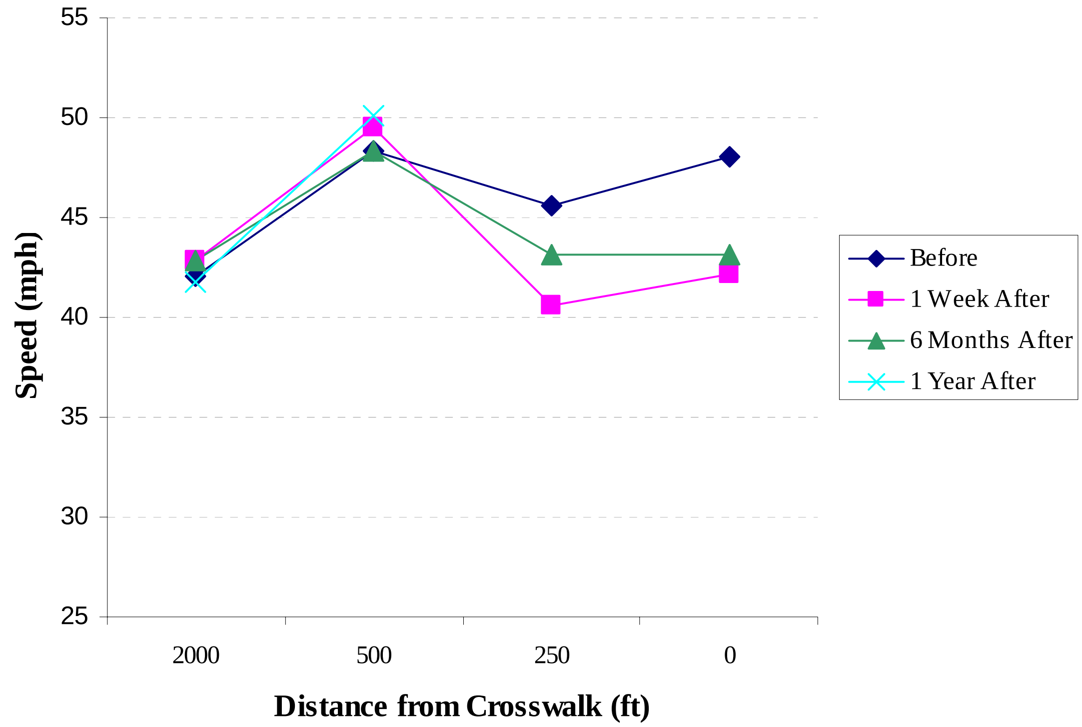

Figure E-3. Southbound High Volume Speed Profiles

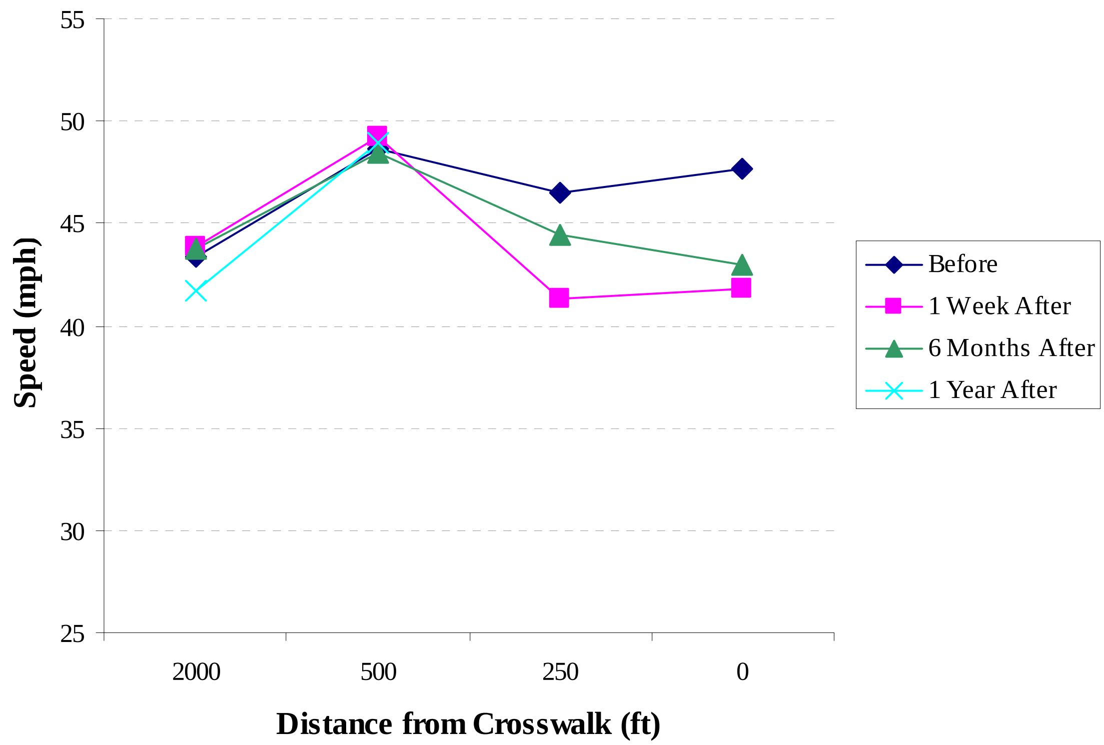

Figure E-4. Southbound Low Volume Speed Profiles

APPENDIX F

BELMONT RIDGE ROAD NORTHBOUND AND SOUTHBOUND DESCRIPTIVE STATISTICS FROM ATR DATA

Table F-1. Northbound Descriptive Statistics

Scenario	Distance from Crosswalk (ft)	N	Mean (mph)	Std. Deviation (mph)	95% Confidence Interval (mph)	
					Lower Bound	Upper Bound
1	850	4475	45.3	7.1	45.1	45.5
	500	4497	45.5	7.3	45.3	45.7
	250	4503	40.4	6.5	40.2	40.6
	0	-	-	-	-	-
2	850	4381	45.5	6.8	45.3	45.8
	500	3280	38.0	6.7	37.7	38.3
	250	3417	45.3	7.9	45.0	45.6
	0	3234	41.3	10.2	41.0	41.5
3	850	4298	40.4	6.6	40.1	40.6
	500	4254	45.5	7.2	45.2	45.7
	250	3887	45.8	9.0	45.5	46.1
	0	3905	39.4	10.8	39.1	39.7
4	850	4242	43.3	7.1	43.0	43.5
	500	4146	43.2	8.7	42.9	43.4
	250	4179	43.4	8.9	43.1	43.6
	0	-	-	-	-	-

Table F-2. Southbound Descriptive Statistics

Scenario	Distance from Crosswalk (ft)	N	Mean (mph)	Std. Deviation (mph)	95% Confidence Interval (mph)	
					Lower Bound	Upper Bound
1	2000	6816	42.9	7.5	42.7	43.1
	500	3044	48.5	8.8	48.2	48.8
	250	6395	45.6	8.5	45.4	45.8
	0	6407	48.0	10.8	47.8	48.3
2	2000	1822	44.2	8.3	43.8	44.6
	500	4237	49.4	8.2	49.1	49.7
	250	4205	39.7	8.8	39.5	40.0
	0	4430	41.2	10.2	41.0	41.5
3	2000	3278	44.0	7.9	43.7	44.3
	500	3126	48.7	8.9	48.4	49.0
	250	3067	42.6	9.8	42.3	42.9
	0	3260	41.7	9.2	41.4	42.0
4	2000	4135	42.9	7.6	42.7	43.2
	500	3193	50.1	9.1	49.8	50.4
	250	-	-	-	-	-
	0	-	-	-	-	-

APPENDIX G

STERLING BOULEVARD NORTHBOUND AND SOUTHBOUND HIGH AND LOW VOLUME SPEED PROFILES FROM ATR DATA

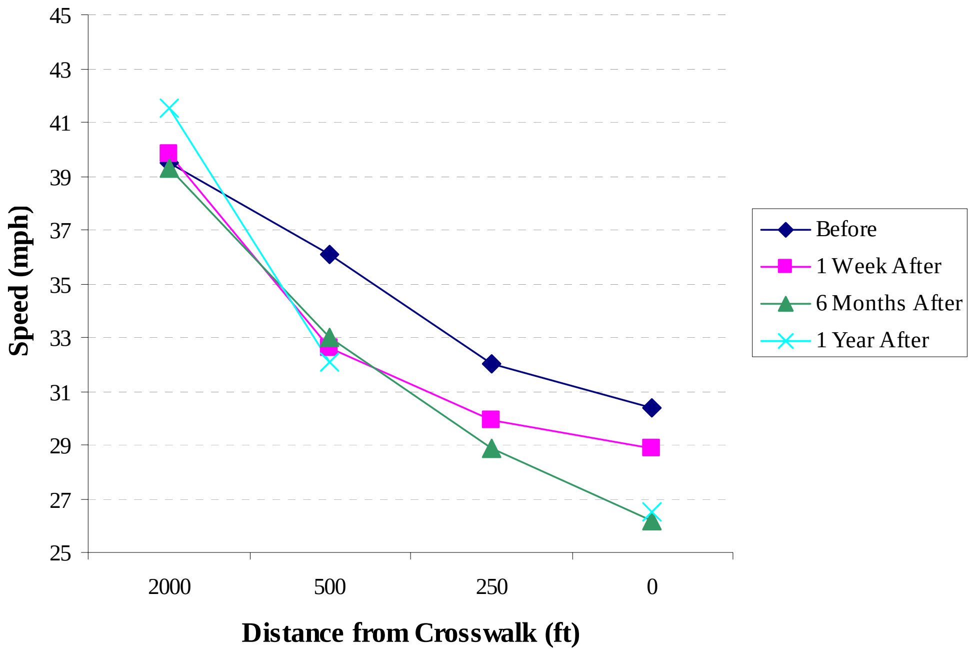

Figure G-1. Eastbound Right Lane High Volume

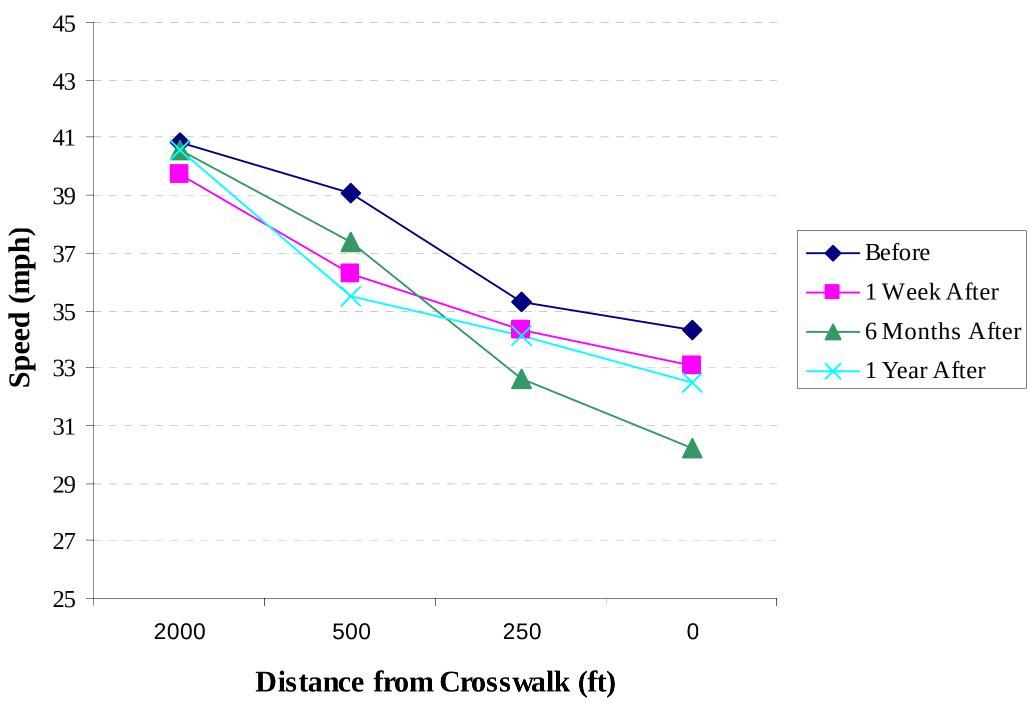

Figure G-2. Eastbound Right Lane Low Volume

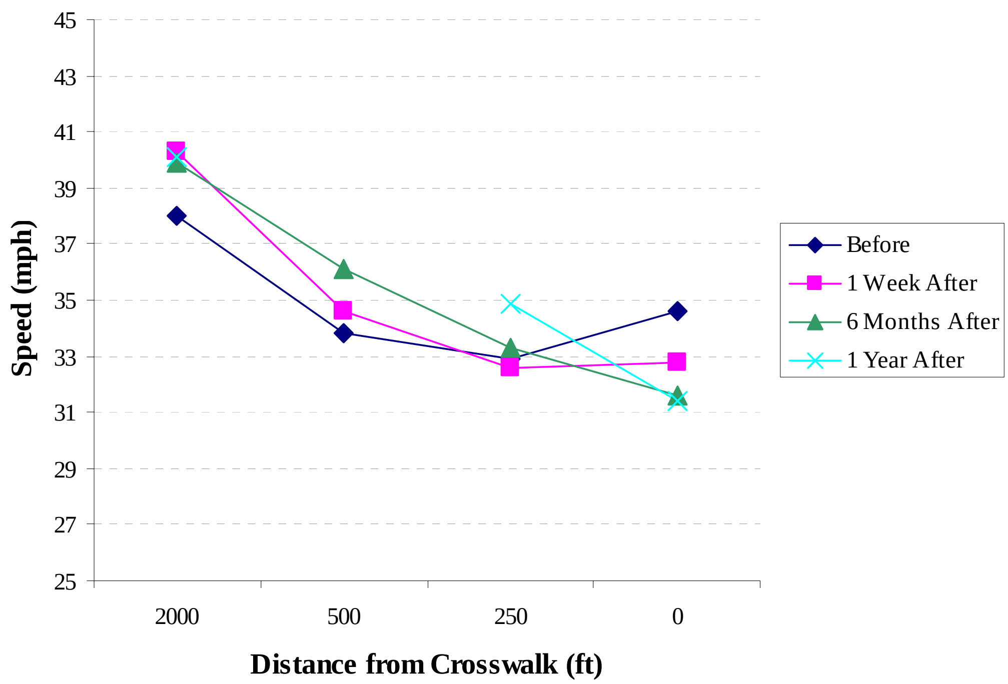

Figure G-3. Eastbound Left Lane High Volume

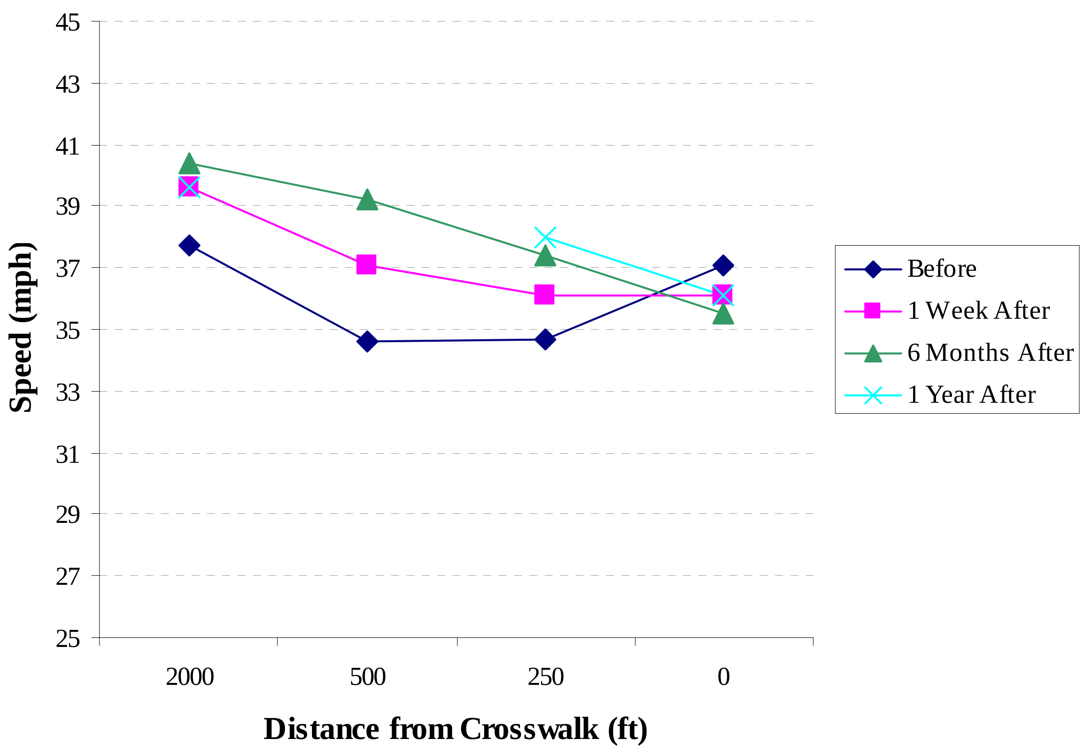

Figure G-4. Eastbound Left Lane Low Volume

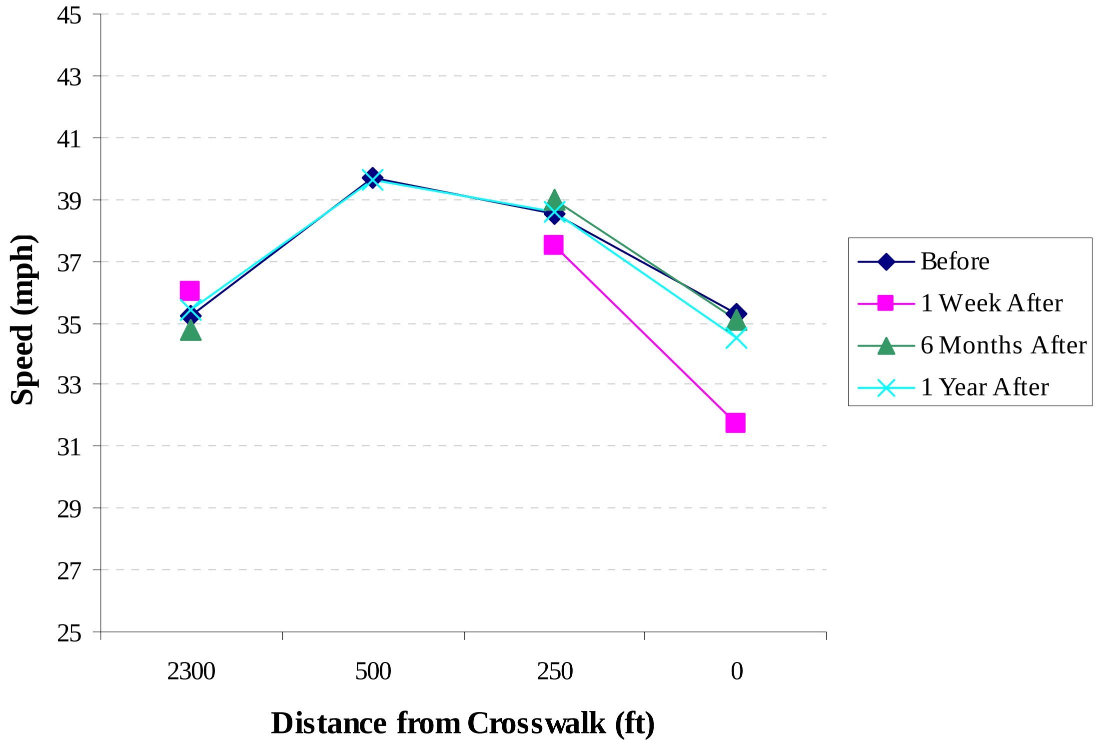

Figure G-5. Westbound Right Lane High Volume

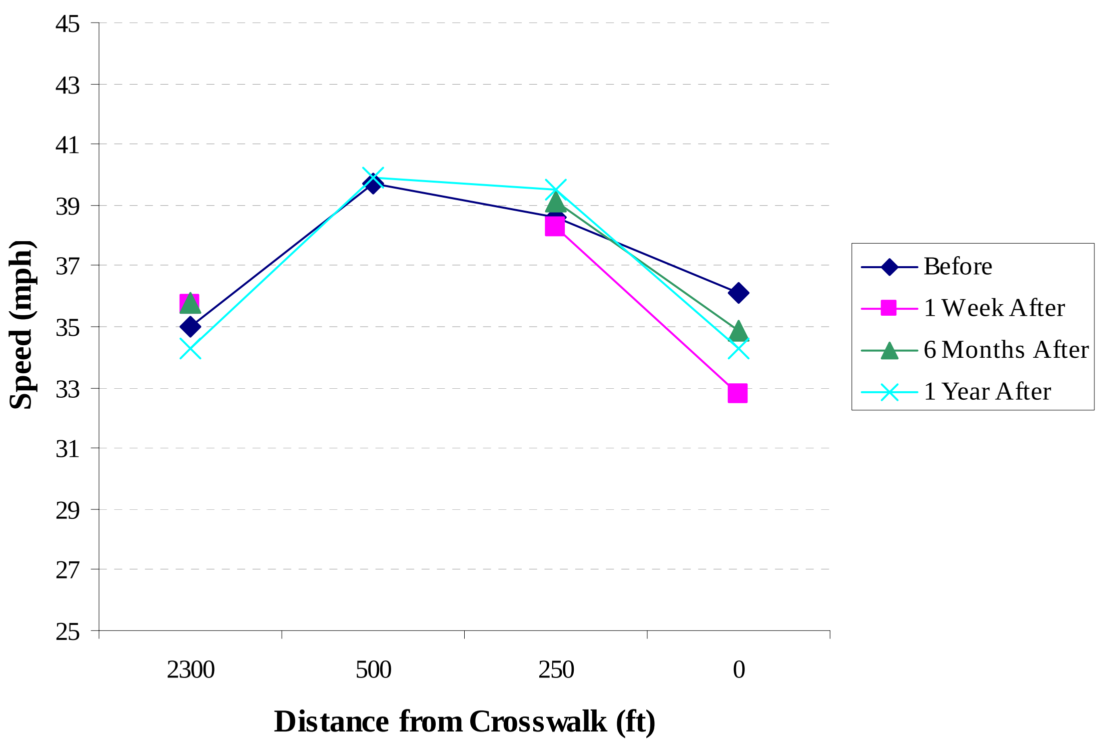

Figure G-6. Westbound Right Lane Low Volume

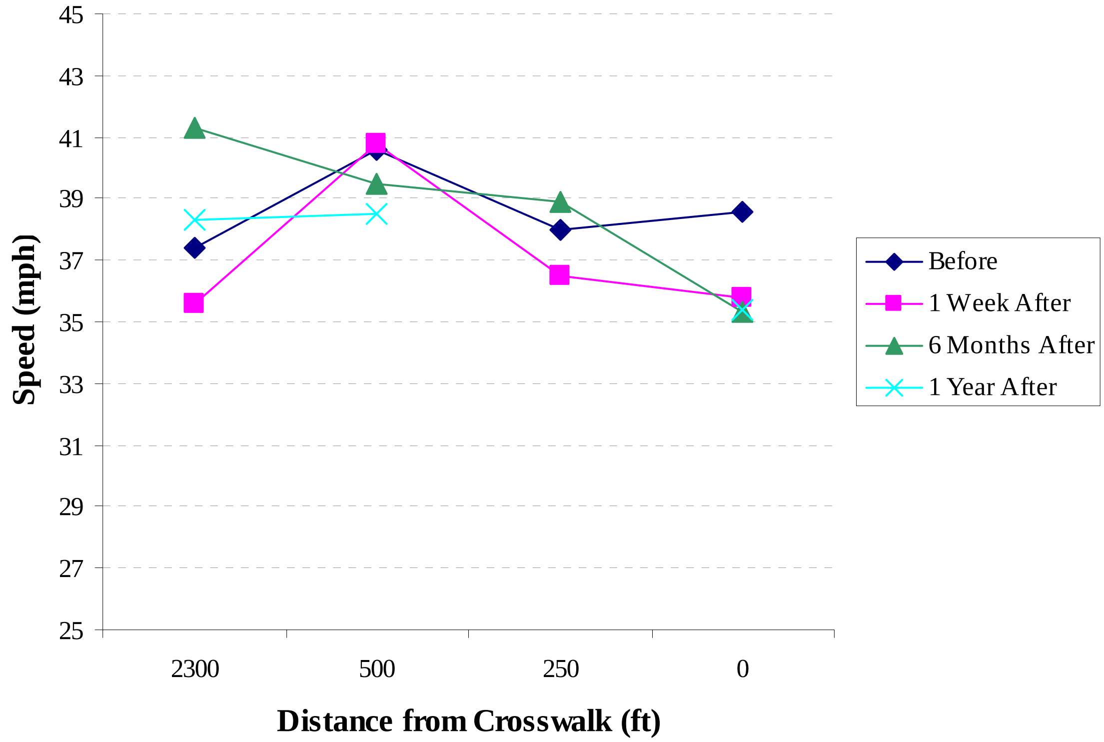

Figure G-7. Westbound Left Lane High Volume

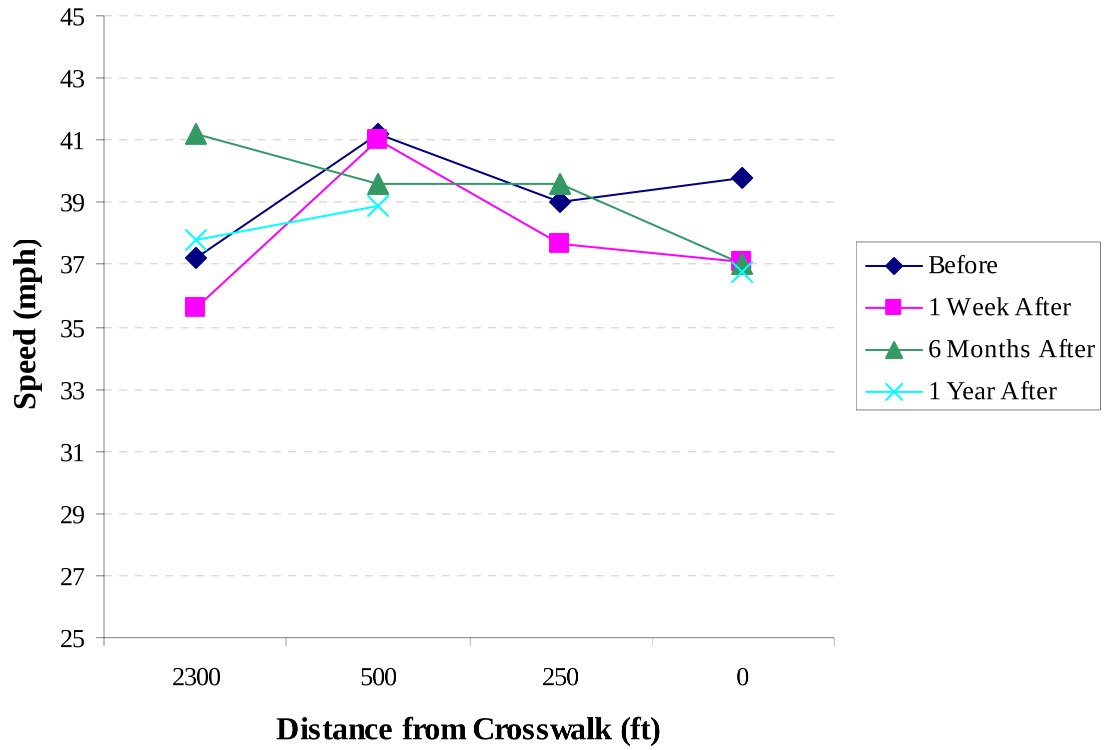

Figure G-8. Westbound Left Lane Low Volume

APPENDIX H

STERLING BOULEVARD EASTBOUND AND WESTBOUND DESCRIPTIVE STATISTICS FROM ATR DATA

Table H-1. Eastbound Right Lane Descriptive Statistics

Scenario	Distance from Crosswalk (ft)	N	Mean (mph)	Std. Deviation (mph)	95% Confidence Interval (mph)	
					Lower Bound	Upper Bound
1	2000	7281	41.6	6.8	41.4	41.7
	500	7070	38.5	7.2	38.4	38.7
	250	7744	35.3	6.5	35.1	35.4
	0	7266	34.2	6.5	34.1	34.4
2	2000	2099	40.0	6.5	39.7	40.2
	500	7315	35.4	6.7	35.2	35.5
	250	8016	34.3	6.4	34.1	34.4
	0	7987	33.1	6.6	32.9	33.2
3	2000	6328	41.4	6.5	41.2	41.5
	500	6107	35.9	6.9	35.7	36.1
	250	6531	32.6	6.6	32.4	32.7
	0	6364	28.8	6.1	28.6	28.9
4	2000	6218	41.9	6.6	41.7	42.1
	500	6067	35.1	6.3	35.0	35.3
	250	-	-	-	-	-
	0	6023	29.6	9.5	29.4	29.8

Table H-2. Eastbound Left Lane Descriptive Statistics

Scenario	Distance from Crosswalk (ft)	N	Mean (mph)	Std. Deviation (mph)	95% Confidence Interval (mph)	
					Lower Bound	Upper Bound
1	2000	4554	40.1	7.5	39.9	40.3
	500	5413	35.7	6.1	35.6	35.9
	250	5599	35.8	6.2	35.7	36.0
	0	5100	38.2	6.7	38.0	38.4
2	2000	5000	41.2	7.2	41.1	41.4
	500	5409	37.7	6.9	37.5	37.9
	250	5773	36.8	6.6	36.6	36.9
	0	5326	37.1	6.9	36.9	37.3
3	2000	4228	41.9	6.9	41.7	42.2
	500	4713	39.0	7.5	38.8	39.2
	250	4915	37.2	6.9	37.0	37.4
	0	4489	35.3	6.9	35.1	35.5
4	2000	4314	41.6	6.9	41.3	41.8
	500	-	-	7.6		
	250	4728	38.8	8.9	38.6	39.1
	0	4628	35.3	8.3	35.1	35.6

Table H-3. Westbound Right Lane Descriptive Statistics

Scenario	Distance from Crosswalk (ft)	N	Mean (mph)	Std. Deviation (mph)	95% Confidence Interval (mph)	
					Lower Bound	Upper Bound
1	2300	6291	36.3	5.5	36.1	36.4
	500	6182	41.3	6.6	41.2	41.5
	250	6358	41.2	6.9	40.0	40.4
	0	6789	36.6	6.1	36.4	36.7
2	2300	6667	36.3	5.6	36.2	36.5
	500	-	-	-	-	-
	250	6645	39.2	7.0	39.0	39.3
	0	7099	33.1	7.4	32.9	33.2
3	2300	2486	36.3	8.1	36.0	36.5
	500	-	-	-	-	-
	250	5436	39.9	6.3	39.7	40.1
	0	5674	35.8	5.4	35.7	36.0
4	2300	5437	35.5	6.2	35.3	35.7
	500	5254	40.3	7.8	40.1	40.5
	250	5056	39.8	7.6	39.6	40.0
	0	5917	33.8	8.9	33.6	33.9

Table H-4. Westbound Left Lane Descriptive Statistics

Scenario	Distance from Crosswalk (ft)	N	Mean (mph)	Std. Deviation (mph)	95% Confidence Interval (mph)	
					Lower Bound	Upper Bound
1	2300	5420	37.8	5.6	37.6	38.0
	500	4934	42.4	9.6	42.2	42.6
	250	5163	40.1	8.0	39.9	40.3
	0	5754	40.1	6.6	39.9	40.3
2	2300	5611	35.7	5.4	35.6	35.9
	500	5648	41.8	6.6	41.6	42.0
	250	5728	38.2	7.8	38.1	38.4
	0	5944	37.2	7.1	37.0	37.4
3	2300	4742	42.1	6.5	41.9	42.3
	500	4695	40.0	6.3	39.8	40.2
	250	4616	39.7	8.4	39.4	39.9
	0	4917	36.5	7.5	36.3	36.7
4	2300	4612	38.9	6.1	38.7	39.1
	500	4634	38.3	7.3	38.1	38.5
	250	-	-	-	-	-
	0	4885	35.9	8.2	35.7	36.1

APPENDIX I

BELMONT RIDGE ROAD NORTHBOUND AND SOUTHBOUND DESCRIPTIVE STATISTICS FROM LIDAR DATA

Table I-1. Northbound Descriptive Statistics

Scenario	Distance from Crosswalk (ft)	N	Mean (mph)	Std. Deviation (mph)	95% Confidence Interval (mph)	
					Lower Bound	Upper Bound
1	500-401	110	43.7	3.4	43.0	44.5
	400-301	156	44.0	3.3	43.4	44.6
	300-201	168	43.6	3.6	43.0	44.1
	200-101	156	43.1	4.1	42.5	43.7
	100-0	146	42.3	4.8	41.7	42.9
2	500-401	128	43.0	4.0	42.2	43.9
	400-301	153	43.1	4.2	42.3	43.9
	300-201	154	42.2	4.7	41.5	43.0
	200-101	125	40.1	5.3	40.1	41.8
	100-0	138	40.4	5.7	39.6	41.2
3	500-401	83	41.6	3.9	40.6	42.6
	400-301	97	42.0	4.2	41.1	42.9
	300-201	95	41.6	4.2	40.7	42.5
	200-101	92	40.7	4.6	39.8	41.7
	100-0	84	39.7	5.3	38.7	40.6
4	500-401	187	42.5	3.5	41.9	43.1
	400-301	192	42.6	3.6	42.0	43.2
	300-201	187	41.8	4.0	41.2	42.4
	200-101	177	41.1	4.7	40.5	41.7
	100-0	175	40.2	4.9	39.6	40.8

Table I-2. Southbound Descriptive Statistics

Scenario	Distance from Crosswalk (ft)	N	Mean (mph)	Std. Deviation (mph)	95% Confidence Interval (mph)	
					Lower Bound	Upper Bound
1	1000-801	137	49.5	3.8	48.8	50.2
	800-601	164	49.6	4.0	49.0	50.3
	600-401	180	49.2	4.0	48.6	49.8
	400-201	175	47.9	4.2	47.3	48.5
	200-0	165	45.0	4.9	44.4	45.6
2	1000-801	71	50.0	4.3	48.9	51.1
	800-601	86	49.8	4.0	48.8	50.8
	600-401	90	48.3	4.3	47.3	49.3
	400-201	83	45.8	4.9	44.7	46.8
	200-0	75	41.8	6.1	40.7	42.9
3	1000-801	99	50.2	3.6	49.3	51.0
	800-601	111	49.9	3.7	49.1	50.8
	600-401	121	48.1	4.0	47.3	48.9
	400-201	116	45.6	5.0	44.8	46.4
	200-0	109	42.1	5.7	41.2	42.9
4	1000-801	117	48.7	3.7	47.9	49.6
	800-601	152	48.0	4.1	47.2	48.7
	600-401	154	46.3	4.1	45.6	47.1
	400-201	150	43.8	4.8	43.0	44.5
	200-0	132	39.3	6.2	38.5	40.1

APPENDIX J

STERLING BOULEVARD EASTBOUND AND WESTBOUND DESCRIPTIVE STATISTICS FROM LIDAR DATA

Table J-1. Eastbound Descriptive Statistics

Scenario	Distance from Crosswalk (ft)	N	Mean (mph)	Std. Deviation (mph)	95% Confidence Interval (mph)	
					Lower Bound	Upper Bound
1	300-201	182	36.1	3.8	35.5	36.7
	200-101	208	38.4	4.1	37.8	38.9
	100-0	107	39.1	4.6	38.4	39.9
2	300-201	159	35.7	3.5	35.1	36.3
	200-101	176	36.7	3.9	36.1	37.3
	100-0	167	36.3	4.0	35.7	36.9
3	300-201	113	36.5	3.3	35.8	37.2
	200-101	139	38.4	3.7	37.8	39.0
	100-0	137	38.2	4.0	37.5	38.8
4	300-201	154	36.8	3.4	36.2	37.3
	200-101	194	38.2	3.7	37.7	38.7
	100-0	183	38.2	4.1	37.7	38.8

Table J-2. Westbound Descriptive Statistics

Scenario	Distance from Crosswalk (ft)	N	Mean (mph)	Std. Deviation (mph)	95% Confidence Interval (mph)	
					Lower Bound	Upper Bound
1	500-401	203	40.9	3.7	40.4	41.4
	400-301	213	40.9	3.7	40.4	41.4
	300-201	216	40.5	3.7	40.0	41.0
	200-101	200	40.1	3.6	39.6	40.7
	100-0	139	40.2	3.5	39.6	40.8
2	500-401	180	39.3	3.8	38.7	39.9
	400-301	198	39.8	4.0	39.2	40.4
	300-201	195	39.4	4.2	38.8	40.0
	200-101	189	38.7	4.3	38.1	39.3
	100-0	175	38.2	4.3	37.6	38.8
3	500-401	166	40.2	3.6	39.6	40.7
	400-301	184	40.7	3.6	40.1	41.2
	300-201	182	40.6	3.6	40.1	41.2
	200-101	172	40.1	4.0	39.5	40.6
	100-0	144	39.4	3.9	38.8	40.0
4	500-401	154	39.6	3.9	39.0	40.2
	400-301	173	40.4	4.0	39.8	41.0
	300-201	178	40.3	3.9	39.7	40.8
	200-101	168	39.9	3.8	39.3	40.5
	100-0	146	39.2	4.0	38.6	39.8