FINAL REPORT

DEVELOPMENT OF AN ASSESSMENT GUIDE FOR BICYCLE USE OF RIGHT SHOULDERS ON CONTROLLED ACCESS FACILITIES IN VIRGINIA

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(A partnership of the Virginia Department of Transportation
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DISCLAIMER

ABSTRACT

The Commonwealth Transportation Board (CTB) adopted the Policy for Integrating Bicycle and Pedestrian Accommodations in 2004 and this policy was designed to ensure that bicycle and pedestrian needs are accommodated through the Virginia Department of Transportation's (VDOT) construction, operations, and maintenance programs. Currently, Virginia lacks objective criteria guiding to determine when bicycle use of controlled access facilities should be permitted or prohibited.

The purpose of this research was to develop a guide to help VDOT determine when bicycle use of the right shoulders of controlled access facilities in Virginia is appropriate from a safety standpoint. Bicyclists are expected to use only the shoulders of such facilities due to the high speeds of motor vehicle traffic. The scope of this research was limited to state controlled access highways and did not address secondary roads.

The Virginia crash data included relatively few crashes involving bicyclists using the controlled access facilities implying bicycle use of these facilities appear to be safe in Virginia. Unfortunately, the number of bicycles using the facilities is not known so crashes relative to exposure is unavailable. Additionally, an underreporting of bicycle crashes may exist. Additional crash analyses were performed using "run-off-right" crashes as a surrogate since they are considered to be the most immediate threat to bicyclists on the right shoulders. Traffic volume and shoulder width would affect potential occurrence of bicycle-vehicle crashes on the right shoulders of the controlled access facilities while urban/rural classification, speed limit, and the number of intersections would not.

This research proposed a guide for determining where bicycle use of controlled access highways in Virginia is permissible from a safety standpoint. The guide was developed based on reviews of relevant design guides and the state of practice, theoretical analysis of stopping sight distance for bicycles, and empirical analysis of crash, traffic, and geometric data. Thus, the guide is considered to be reliable and valid. However, the guide should not serve as a warrant or requirement.

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INTRODUCTION

On March 18, 2004 the Commonwealth Transportation Board (CTB) adopted the *Policy for Integrating Bicycle and Pedestrian Accommodations* (VDOT, 2004). This policy was designed to ensure that bicycle and pedestrian needs are considered through Virginia Department of Transportation's (VDOT) construction, operations, and maintenance programs. Unless there is compelling evidence that would recommend otherwise (such as excessive costs or high crash risk), the language of Section 3.4 of the Policy implies that serious consideration be given to meet bicyclist and pedestrian needs. The full text of the policy is found in Appendix A.

This context is especially important when considering the special case of controlled access facilities. Currently, bicyclists are allowed to legally ride on all roads in Virginia unless prohibited by the CTB. Although §46.2-808 of the *Code of Virginia* clearly gives the CTB authority to "prohibit certain uses of controlled access highways," including use by persons riding bicycles, the 2004 Policy implies that this regulation should not be taken lightly. In particular, Section 4.0 of the Policy states that:

> Procedures, guidelines, and best practices will be developed or revised to implement the provisions set forth in this policy. For example, objective criteria will be prepared to guide decisions on the restriction of bicycle and pedestrian use of access-controlled facilities.

Definition and advantages of access control are stated on page 2-70 of "A Policy on Geometric Design of Highways and Streets" (AASHTO, 2011) (referred to as AASHTO's Green Book hereinafter) as:

> Regulating access is called "access control." It is achieved through the regulation of public access rights to and from properties abutting the highway facilities… The principal advantages of controlling access are the preservation or improvement of service and the reduction of crash frequency and severity.
>
> The functional advantage of providing access control on a street or highway is the management of the interference with through traffic…

Examples of controlled access facilities in Virginia include interstate highways, some portions of primary, and occasionally secondary highways. There are estimated 1,500 centerline miles of fully controlled access highways in the Commonwealth—about 1,100 miles on the interstate system and 400 miles on the primary system. Bicyclists are prohibited from using interstate highways except when a barrier separated facility is provided as allowed in the *Code of Virginia* §46.2-908.1, amended in 2009. However, it is not as clear which of the fully controlled access primary highway segments have bicycle prohibitions. Further, for those controlled access facilities that allow bicyclists, the number of crashes has not been tabulated. What is known is that statewide on all facilities in 2012, there were 804 bicycle-vehicle crashes (11 bicyclists killed and 790 injured) (DMV, 2013).

Virginia lacks objective criteria guiding to determine when bicycle use of controlled access facilities should be permitted or prohibited. Such criteria are needed by VDOT staff and the CTB for several reasons. First, the VDOT staff is called upon to advise the CTB regarding which controlled access facilities should prohibit bicycle use, and thus needs guidance upon which to base such recommendations. Second, highway segments currently prohibited for bicycle use will be evaluated to determine if permitting bicycles on shoulders of those segments is appropriate, under VDOT's broader efforts to promote bicycle accommodations. Third, members of the public are aware of the March 18, 2004 policy and continue consequently beginning to ask VDOT and the CTB to clarify the rationale behind bicycle prohibitions on specific controlled access facilities.

PURPOSE AND SCOPE

The *purpose* of this research was to develop a guide to help VDOT determine when bicycle use of the right shoulders of controlled access facilities in Virginia is appropriate from a safety standpoint. Bicyclists are expected to use only the shoulders of such facilities due to the high speeds of motor vehicle traffic.

The *scope* of this research was limited to state controlled access highways and did not address secondary roads.

METHODS

The research involved the following tasks:

1. *Identify the controlled access facilities that currently explicitly prohibit or permit bicycle use.* An inventory of both partially and fully controlled access facilities where bicycling is currently prohibited was prepared with the help of personnel from the nine VDOT districts. VDOT's Highway Traffic Records Inventory System (HTRIS) database, in conjunction with archived text of CTB resolutions, was initially utilized to identify prohibited segments of controlled access facilities. Specific start and end points for each prohibited section were manually identified by district staff.

2. *Conduct a literature review.* Relevant literature concerning bicycle use on controlled access facilities was collected and reviewed. Critical factors that were likely to influence safety and operations of bicycles on shoulders were identified and their effects were summarized. Also, design or policy guides that can serve as an initial guide for this study were reviewed, including VDOT's Road Design Manual (VDOT, 2005).

3. *Examine suitability of stopping sight distance for bicycles.* Stopping sight distances (the distance a vehicle or bicycle will travel while decelerating to a stop after recognizing an obstacle in its path) suitable for motor vehicles were examined to determine if they are also sufficient for bicycles. Since braking characteristics, especially deceleration rates, are different, it is crucial to examine if highway shoulders built to satisfy stopping sight distances for motor vehicles also satisfy those distances for bicycles. Since bicycle speeds on varying grades are not known, 30 mph was assumed to calculate stopping sight distances required for bicycles.

4. *Develop database for data analysis*. The collected prohibition data were combined with roadway inventory, crash, and traffic volume data using the HTRIS link system. Shoulder width data that have been maintained by VDOT's Maintenance Division were obtained. However, because this data was based on location identifiers that were different from the HTRIS link system, it was not compatible with the combined database. Using an algorithm modified from one developed by VDOT's Maintenance Division, the combined database and the shoulder width data were merged. This final database contains geometric characteristics (e.g., number of lanes and shoulder width), use information (e.g., speed limit and urban/rural area type), traffic volume (annual average daily traffic), and bicycle prohibition status.

5. *Use historical data to estimate the crash risk.* The purpose of this task was to predict the safety impact of factors identified in Task 2 as critical for bicyclists on shoulders of controlled access highways. The database created in Task 4 was used in this analysis. A general additive model (GAM) (see Hastie and Tibshirani [1990] for details) was used to propose appropriate functional forms for model development (see Appendix B for descriptions and results of GAM) and negative binomial (NB) regression models were developed for different types of traffic crashes such as run-off-right and single-vehicle crash types.

6. *Develop a framework for determining when bicycle use of the right shoulder of controlled access facilities is appropriate*. Using the findings from the literature review in Task 2, examination of stopping sight distances in Task 3, and crash data analysis in Task 5, a guide was developed to determine those segments of controlled access highways for which bicycle use shoulder be allowed. Nine steps leading to the minimum shoulder widths for the guide were established (See Appendix C).

RESULTS AND DISCUSSION

Definitions

During the literature review, significant confusion was found to be associated with definitions of elements related to bicycle travel. Clarifications on such definitions are made below.

Shoulder

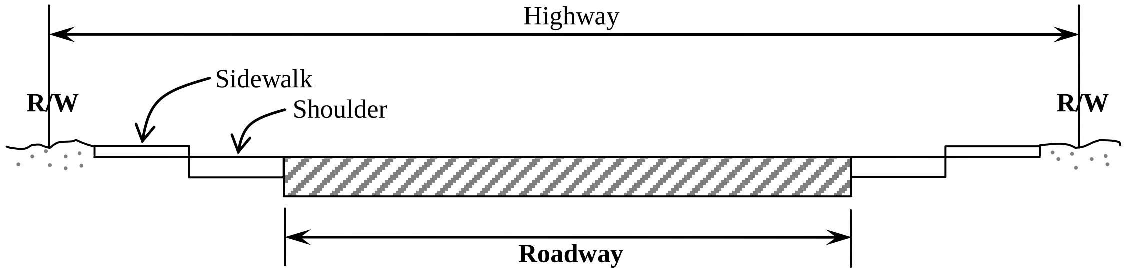
Shoulder refers to "[t]he portion of the roadway contiguous with the traveled way for accommodation of stopped vehicles, for emergency use and for lateral support of sub-base, base and surface courses" in Guide for the Development of Bicycle Facilities (AASHTO, 2012). A more detailed definition is found in Asset Management's Best Practices Manual (VDOT, n.d.), "The term 'shoulder' refers to the area between the pavement edge and the ditch or fill edge. The purpose of the shoulder is to provide stability to the base, convey water away from the pavement edge, provide emergency parking area for vehicles, and provide an area for bicycle and pedestrian traffic. The emergency use of the shoulder cannot be over-stressed. Vehicles should at all times be able to move onto and off the shoulder with ease and safety."

Highway vs. Roadway

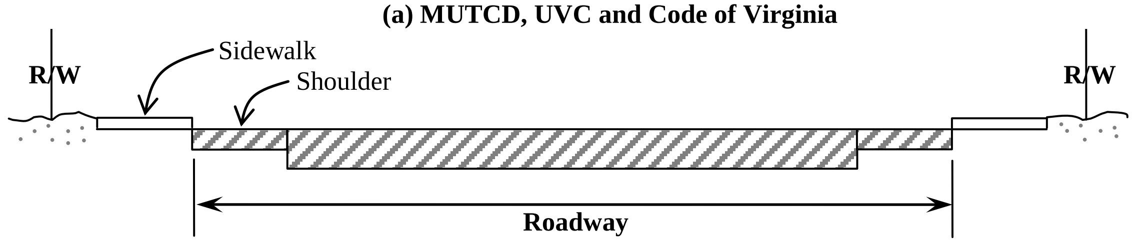
Differences in the definition of a highway and a roadway make applications of some bicycle design guides difficult. Figure 1 shows different definitions of a highway and a roadway found in relevant guides and codes. According to the Manual on Uniform Traffic Control Devices (MUTCD) (FHWA, 2012), a *highway* is "a general term for denoting a public way for purposes of travel by vehicular travel, including the entire area within the right-of-way" while a *roadway* is "that portion of a highway improved, designed, or ordinarily used for vehicular travel and parking lanes, but exclusive of the sidewalk, berm, or shoulder even though such sidewalk, berm, or shoulder is used by persons riding bicycles or other human-powered vehicles": this same definition was found in the Uniform Vehicle Code (UVC) (FHWA, 1994a).

The *Code of Virginia* provides similar definitions to the above. According to § 46.2-100 of the *Code*, a highway is defined as "the entire width between the boundary lines of every way or place open to the use of the public for purposes of vehicular travel in the Commonwealth…" A roadway is defined as "portion of a highway improved, designed, or ordinarily used for vehicular travel, exclusive of the shoulder." According to the definitions in the MUTCD, UVC, and the *Code of Virginia*, a roadway *does not* include shoulders while a highway *does*.

However, according to the definitions in design guides and documents published by American Association of State Highway and Transportation Officials (AASHTO), a roadway *does include* shoulders. AASHTO defines a roadway as the portion of a highway, including shoulders, for vehicular use in AASHTO's Green Book (2011). AASHTO's "Guide for the Development of Bicycle Facilities" (2012) (referred to as AASHTO's Bike Design Guide hereinafter) adopted the same definition of a roadway as in AASHTO's Green Book (2011) and used the definition of a highway found in the MUTCD (FHWA, 2012).



(a) MUTCD, UVC and Code of Virginia



(b) AASHTO

Note: R/W represents right of way.

Figure 1. Difference in definitions of highway and roadway.

Since the guide developed in this study could be used by planners, policy makers, traffic engineers, and road designers, a comprehensive term was needed for this report. Thus, a *highway* was used throughout this report since it includes shoulders in all the above guides and manuals. The use of this term will also allow the report to address the space between the shoulder and the right of way line as well as correspond to the legal text used when the CTB makes a Limited Access Resolution.

Full vs. Partial Control of Access

According to the AASHTO's Green Book (2011), full control of access denotes that "preference is given to through traffic by providing access connections by means of ramps with only selected public roads and by prohibiting crossings at grade and direct private driveway connections." Partial control of access is used when "preference is given to through traffic to a degree. Access connection, which may be at-grade or grade-separated, is provided with selected public roads, and private driveways."

More practical definitions are used in practice in VDOT's Maintenance Division[1]. Fully controlled access facilities are highways that have all traffic movements controlled through the use of ramps and loops at grade separated interchanges. Signals may exist at some ramp intersections but they will be on the highways interchanging with an interstate highway, not the interstate itself. Partially controlled facilities are designed to keep the number of intersecting highways to a minimum and accessibility is directed to a main intersection. The main intersection is usually on divided highways and traffic movements are controlled through the use of signals. Since information collected for data analysis regarding access control types, which are stored in VDOT's HTRIS database, follows these practical definitions, VDOT's definitions of *full and partial access controls* described above were used throughout this report.

[1] Personal communication with Ann Austin, Maintenance Division of VDOT Central Office.

Bicycle

AASHTO's Bike Design Guide (2012) defines a bicycle as "every vehicle propelled solely by human power upon which any person may ride, having two tandem wheels, except scooters and similar devices." The term bicycle also includes "three- and four-wheeled human-powered vehicles, but not tricycles for children." This report adopted this definition of *bicycle*.

Design Bicyclist

The FHWA's report (FHWA, 1994a) proposed use of three design bicyclist groups to help road designers in determining the impact of different facility types and roadway conditions on bicyclists. The three design bicyclist groups were adopted in FHWA's "Selection Roadway Design Treatments to Accommodate Bicycles" (FHWA, 1994b), referred to as FHWA's Bike Design Guide hereinafter, and were noted in AASHTO's Bike Design Guide (2012). They are defined as follows:

- Group A: Advanced bicyclists (experienced)
  Advanced or experienced riders are generally using their bicycles as they would a motor vehicle. They are riding for convenience and speed and want direct access to destinations with a minimum of detour or delay. They are typically comfortable riding with motor vehicle traffic; however, they need sufficient operating space on the traveled way or shoulder to eliminate the need for either themselves or a passing motor vehicle to shift position.

- Group B: Basic bicyclists (casual, novice, occasional)
  Basic or less confident adult riders may also be using their bicycles for transportation purposes, e.g., to get to the store or to visit friends, but prefer to avoid roads with fast and busy motor vehicle traffic unless there is ample roadway width to allow easy overtaking by faster motor vehicles. Thus, basic riders are comfortable riding on neighborhood streets and shared use paths and prefer designated facilities such as bike lanes or wide shoulder lanes on busier streets.

- Group C: Children (pre-teen)
  Children, riding on their own or with their parents, may not travel as fast as their adult counterparts but still require access to key destinations in their community, such as schools, convenience stores and recreational facilities. Residential streets with low motor vehicle speeds, linked with shared use paths and busier streets with well-defined pavement markings between bicycles and motor vehicles can accommodate children without encouraging them to ride in the travel lane of major arterials.

More bicyclists are expected to use highways as more facilities are designed and built to accommodate bicycles. Policy initiatives are also encouraging increases in bicycle travel (e.g., VDOT, 2004; FHWA, 1994b). Therefore, it is preferable for design treatments to address the needs of both experienced and less experienced bicyclists. In this respect, Group B/C bicyclists are typically selected as the design bicyclist. FHWA's Bike Design Guide (1994b) also determined Group B/C bicyclists to be a design bicyclist for facility design for the same reason.

However, it should be recognized that the purpose of this report is not to design a designated bicycle facility. Instead, it is to decide when it is appropriate to allow bicycle use of existing controlled access facilities.

As was noted in the introduction, currently a bicyclist can legally ride on any road in Virginia unless prohibited. They do, however, ride at their own risk, making a judgment whether their skill level is sufficient for the conditions on that particular road. As noted in VDOT's Road Design Manual (2005), "For example, a four-lane divided highway with 12-foot travel lanes, no shoulder and a 55 mph speed limit will attract only the most confident of riders. The same road with a 5-foot shoulder or bike lane might provide sufficient 'comfortable operating space' for many more adult riders, but would still not be comfortable for children or less confident adults. This latter group might only be accommodated through an alternative route using neighborhood streets linked by short sections of shared use path. If such an alternative route is provided and the four-lane road has a continuous paved shoulder, most experienced and many casual adult riders will continue to use the shoulder for the sake of speed and convenience." When a prohibition is imposed, it will indicate that the facility is unsafe for all bicyclists, even the highly skilled Group A bicyclists. VDOT's Road Design Manual (2005) recommends the use of Group A bicyclists for designing bike facilities on rural and some urban sections of highways with scattered development that are operationally similar to controlled access highways, the focus of this study. Therefore, for the purpose of this study, the *Group A bicyclist* was selected as *the determining bicyclist for the guide*.

Safety Considerations for Bicycles on Shoulders

The safety considerations of bicycle operations on shoulders was examined through three distinct approaches, (1) review of relevant publications, (2) analysis of stopping sight distance, and (3) analysis of surrogate crash measures.

Review of Relevant Publications

Reports, guides, and manuals (AASHTO, 2012; Ferrara and Gibby, 2001; FHWA, 1977; FHWA, 1994b; FHWA, 1998; FHWA, 2006; Landis et al., 1997; Smith, 1975; VDOT, 2005; Walton et al., 2005) relevant to bicycle operations and safety on shoulders were reviewed, and among them, two bicycle facility design guides (FHWA, 1994b; AASHTO, 2012) were found to be the most useful for developing the guide. Based on the literature surveyed, the following factors were found to be critical for safe operations of bicyclists on shoulders:

- shoulder width
- traffic volume
- traffic speed
- presence of heavy vehicles
- sight distance
- presence of intersections
- vehicle induced wind force
- presence of rumble strips
- other factors (e.g., grade, surface, and access)

The first six factors were reported as the most often cited factors influencing bicycle operations (FHWA, 1994b). The above factors were considered for developing the bicycle guide and findings regarding each of the factors are summarized below.

Shoulder Width

The shoulder width was reported as the most important factor regarding the safety and operations of bicyclists on shoulders, especially in terms of bicyclists' comfort (FHWA, 1995). According to bicycle facility design guides (e.g., FHWA, 1994b; AASHTO, 2011), 4 feet is the minimum width of a paved shoulder when designing a designated bicycle facility and many state highway agencies have adopted this minimum width. The shoulder width should be increased as an adjacent vehicle speed increases and/or heavy vehicle traffic increases. Only FHWA's Bike Design Guide (1994b) provides explicit guidance on how the shoulder width should increase with increasing speed or heavy vehicle volume. However, AASHTO's Bike Design Guide (2012) states that any shoulder width is better than no shoulders at all. Because this study defines Group A bicyclists as the determining ones for the guide and focuses on controlled access highways where no street parking is present, two tables in the FHWA's Bike Design Guide (1994b) were found to be especially relevant to this study, one for urban sections with no parking and the other for rural sections.

These are presented as Tables 1 and 2, and provide recommended bicycle facility treatments for Group A bicyclists by four criteria, speeds, traffic volume, sight distance, and presence of heavy vehicles, each of which is discussed later. The presence of heavy vehicles is defined as approximately 30 or more vehicles per hour. For example, using Table 2 for a rural road with AADT less than 2,000, inadequate sight distance, more than 30 heavy vehicles (trucks, buses, and recreational vehicles) per hour, and an average operating speed of 55 mph, a minimum shoulder width of 6 feet would be recommended for a design treatment accommodating bicycles. The two tables are also included in VDOT's Road Design Manual (2005).

Table 1. Recommended Facility Type for Group A Bicyclists in Urban Section, No Parking

Average motor vehicle operating speed	Average annual daily traffic (AADT)											
	<2,000				2,000-10,000				>10,000			
	Sight distance				Sight distance				Sight distance			
	Adequate		Inadequate		Adequate		Inadequate		Adequate		Inadequate	
		Truck, bus, rv				Truck, bus, rv				Truck, bus, rv		
<30 mph	sl 12	sl 12	wc 14	wc 14	sl 12	wc 14	wc 14	wc 14	wc 14	wc 14	wc 14	wc 14
30-40 mph	wc 14	wc 14	wc 15	wc 15	wc 14	wc 15	wc 15	wc 15	wc 14	wc 15	wc 15	wc 15
41-50 mph	wc 15	wc 15	wc 15	wc 15	wc 15	wc 15	sh 6	sh 6	wc 15	wc 15	sh 6	sh 6
>50 mph	sh 6	sh 6	sh 6	sh 6	sh 6	sh 6	sh 6	sh 6	sh 6	sh 6	sh 6	sh 6

Source: Table 9 in FHWA's "Selecting Roadway Design Treatments to Accommodate Bicycles" (1994b)
Note: sl=shared lane; wc=wide curb lane; sh=shoulder; number in feet

Table 2. Recommended Facility Type for Group A Bicyclists in Rural Section

Average motor vehicle operating speed	Average annual daily traffic (AADT)											
	<2,000				2,000-10,000				>10,000			
	Sight distance				Sight distance				Sight distance			
	Adequate		Inadequate		Adequate		Inadequate		Adequate		Inadequate	
		Truck, bus, rv				Truck, bus, rv				Truck, bus, rv		
<30 mph	sl 12	sl 12	wc 14	wc 14	sl 12	wc 14	wc 14	wc 14	wc 14	wc 14	sh 4	sh 4
30-40 mph	wc 14	wc 14	sh 4	sh 4	wc 14	wc 15	sh 4	sh 4	sh 4	sh 4	sh 4	sh 4
41-50 mph	sh 4	sh 4	sh 4	sh 4	sh 6	sh 6	sh 6	sh 6	sh 6	sh 6	sh 6	sh 6
>50 mph	sh 4	sh 6	sh 6	sh 4	sh 6	sh 6	sh 6	sh 6	sh 6	sh 6	sh 6	sh 6

Source: Table 11 in FHWA's "Selecting Roadway Design Treatments to Accommodate Bicycles" (1994b)
Note: sl=shared lane; wc=wide curb lane; sh=shoulder; number in feet

Traffic Volume

Higher levels of traffic are thought to pose higher potential risk for bicyclists on shoulders because, in general, as traffic volume increases, traffic crashes also increase, which may result in more bicyclist-motor vehicle crashes on shoulders. Also, it is reasonable to assume that as traffic volume increases, more vehicles would stop on the shoulders for various purposes (e.g., emergency stop due to mechanical defects of vehicles), leading to an increased probability of collision between such vehicles and a bicyclist on a shoulder. In general, the majority of bicycle-involved crashes occur at intersections. On controlled access highways, those crashes have either been eliminated (fully controlled) or their frequency is greatly reduced (partially controlled).

FHWA's Bike Design Guide (1994b) grouped AADTs into three levels for recommending minimum shoulder widths for bicycle facilities; <2,000, 2,000–10,000, and >10,000. However, as stated in the guide, the thresholds were determined based on professional judgment not on empirical data analysis. An empirical assessment using crash data in Virginia was performed in this study to verify suitability of the grouping, and the results are presented in the Analysis of Surrogate Crash Measures section.

Speed

The speed of adjacent traffic is an important factor for safety of bicyclists on shoulders because (1) in a collision between a bicycle and a motor vehicle, injury severity for the cyclist is likely to increase as a motor vehicle speeds increases, (2) higher vehicle speeds adjacent to bicyclists are expected to have a negative impact on the perceived comfort of those users (Landis et al., 1997; FHWA, 1998), and (3) higher vehicle speeds are expected to result in greater wind forces as vehicles pass which could impact the stability of the bicycles (Smith, 1975).

An average operating speed is believed to be a more appropriate indicator of safety than the posted speed limit. However, to obtain the average operating speed, empirical speed data must be collected, and such data may not always be available, especially on new construction.

Therefore, the posted speed limit can be used in these instances as a practical alternative. When evaluating existing highways, an engineer has the option to use the average operating speed depending on the site conditions.

A second aspect of speed should be mentioned. The tables in FHWA's Bike Design Guide (FHWA, 1994b) address low speeds below 30 mph. These speeds are typical of residential streets but not typically found on controlled access highways. Thus, consideration for such low speed categories may not be appropriate for this study. Further discussion of the speed categories can be found later in this report.

Heavy Vehicles

The presence of heavy vehicles including trucks, buses, and recreational vehicles is important with respect to the safety and operations of bicyclists because (1) like increased speeds, the presence of heavy vehicles is anticipated to negatively impact the perceived comfort of bicyclists (Landis et al., 1997) and (2) wind forces caused by heavy vehicles passing bicyclists could cause destabilization of the bicyclists (Smith, 1975). For the purpose of the bicycle facility design tables, FHWA's Bike Design Guide (1994b) defines the regular presence of the heavy vehicles to be approximately 30 or more vehicles per hour.

Sight Distance

Sight distance is often cited as a critical factor especially in situations where bicycles and motor vehicles are mixed and motor vehicles overtake bicycles (FHWA, 1994b). This is of limited concern for this study because bicyclists are expected to use the shoulders as opposed to the travel lanes. However, sight distance, especially stopping sight distance, is an important factor because bicycles have a slower deceleration rate than motor vehicles. In some cases even at low design speeds, although a segment has been constructed satisfying minimum stopping sight distances specified in AASHTO's Green Book (2011) for motor vehicles, bicycles may not have sufficient stopping distance. Theoretical analysis of stopping sight distances for bicycles was performed and the results are reported in the Analysis of Stopping Sight Distance section.

Intersections

When bicycles must cross intersections along their path, the risk of being involved in a collision with a motor vehicle increases. FHWA's Bike Design Guide (1994b) mentions the presence of intersections as one of the six major factors for selecting bicycle design treatments yet does not include it in the five criteria determining the design treatments for bicycles. The guide states that the frequency/number of intersections should be considered for considering bike lanes or separate bike paths.

Wind Force

Lateral aerodynamic wind forces produced by heavy vehicles at a high speed contribute to the instability of bicycles operating nearby. Such forces were found to be proportional to the size and speed of the heavy vehicle and the lateral distance from the bicycle (Walton et al., 2005;

FHWA, 1977). As a heavy vehicle passes a bicycle, a force pushing the bicycle away from the heavy vehicle is followed by a force pulling the bicycle toward the path of the heavy vehicle. Although the forces themselves may not be strong, a rapid change of these forces in a short period of time could cause destabilization.

In 1977, FHWA published Figure 2, showing the lateral wind forces on a bicycle from a passing heavy vehicle. The figure provides guidance on a safe separation distance between the bicycle and the heavy vehicle. As long as at least 4 feet of a separation distance is maintained, the lateral wind forces produced by the heavy vehicle at a passing speed of up to 50 mph should not cause a safety concern for the bicycle. At speeds above 50 mph, additional separation space is needed to avoid bicycle instability. To stay below the tolerance limit of the lateral wind force, 5 and 6 feet separations are required at 55 and 60 mph, respectively. It should be noted that a bicyclist is not likely to operate on the rightmost edge of the shoulder at all times and a truck with the maximum width of 8.5 feet does not occupy the full width of a 12-foot lane.

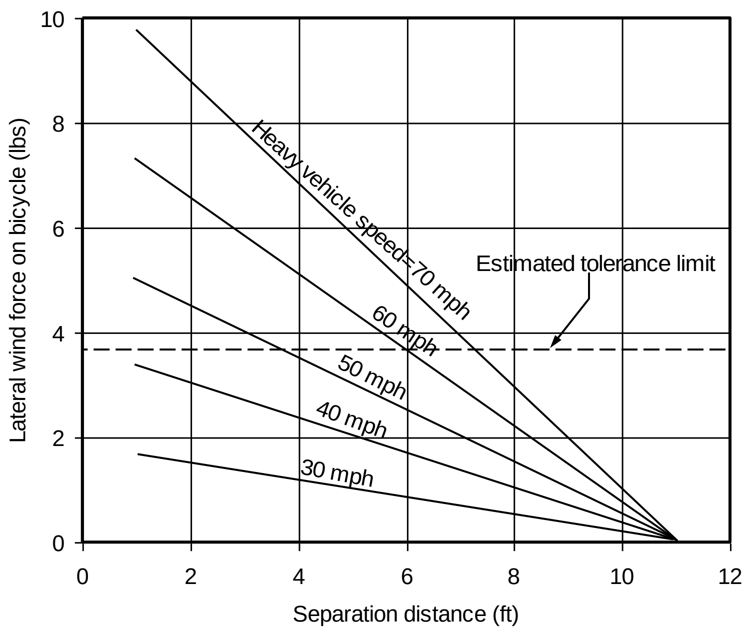


Figure 2. Aerodynamic forces caused by heavy vehicles passing bicycles (Figure 4-8, FHWA, 1977)

Rumble Strips

According to AASHTO's Bike Design Guide (2012), if rumble strips or raised pavement markers are installed, an additional 1 foot of shoulder width from the rumble strip is recommended. Paved shoulder widths should be a minimum 5 feet of ride-able space, free of rumble strips, on freeways (AASHTO, 2012). VDOT recommendations state that if bicycles are permitted on shoulders, the RS-4 (shoulder rumble stripes) or RS-5 (intermittent shoulder rumble strips) should be used since they provide the maximum useable space for bicycles. In general, rumble stripes include paint or tape to provide a visual delineation of the edge of the travel lane while rumble strips do not. Design standards of different rumble strips are found in VDOT Road and Bridge Standards: Section 300–Pavement Items (VDOT, 2008): For example, RS-1 for continuous shoulder rumble strips, RS-4 for continuous shoulder rumble stripes, and RS-5 for intermittent shoulder rumble strips.

Other Factors

Grade has a direct impact on bicycle performance. On a downgrade segment, a bicycle could exceed the maximum speed for safe operations. For example, the braking capability of a bicycle may become significantly reduced on a downgrade segment causing the stopping sight distance of the bicycle to increase. This poses a safety risk to the bicyclist when encountering a stopped vehicle or bicycle on a shoulder. Additionally, on an upgrade segment, the lateral movement of a bicycle is greater than that on level ground.

The surface of a bicycle facility should have smooth pavement and drainage inlets and structures that are appropriate for bicycles. For example, drainage grate inlets and utility covers should be bicycle-compatible so that a bicycle wheel does not fall into a slot in the grate (FHWA, 2006; VDOT, 2005) or they should be located outside of the space needed for a bicycle to operate. Figure 3 shows examples of bicycle-compatible grates. Bicyclist comfort levels were found to be affected greatly by pavement surface conditions (Landis et al., 1997). The same or better quality surface is desirable for bicycles as is provided for motor vehicles.

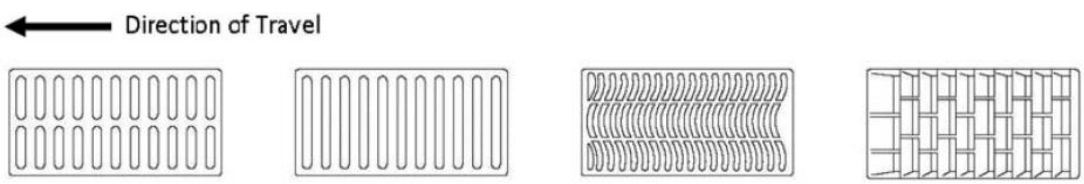


Figure 3. Bicycle-compatible drainage grades (Figure 4-38, AASHTO, 2012).

In rare situations on partially controlled roads, there could be private entrances or private roads leading to a home, farm or even a commercial business. These access points typically exist when the road is historical or one of the early U.S. highway routes. When the road is widened, the construction project normally provides each landowner with an alternate entrance unless it is infeasible, in which case, the original entrance to the partially controlled highway is retained. In most cases, roads providing the only access to a home or business should not include a bicycle prohibition.

Analysis of Stopping Sight Distance

The analysis for stopping sight distance was performed to determine if minimum sight distances for vehicles in AASHTO's Green Book (2011) would suffice for bicycles. AASHTO's Green Book provides the following formula to calculate stopping sight distance (SSD) for motor vehicles:

$$SSD = 1.47Vt + \frac{V^2}{30\left(\frac{a}{g} \pm G\right)} \qquad \text{Eq. (1)}$$

where SSD = stopping sight distance (ft)
V = design speed (mph)
t = brake reaction time (sec), typically 2.5 seconds
a = deceleration rate (ft/s^2)
g = gravitational acceleration (32.2 ft/ s^2)
G = grade (decimal)

Because a friction factor is the deceleration rate divided by the gravitational acceleration ($f = a/g$), the above equation can be expressed as:

$$SSD = 1.47Vt + \frac{V^2}{30(f \pm G)} \qquad \text{Eq. (2)}$$

A deceleration rate of 11.2 ft/s^2 (equivalently, $f = 11.2/32.2 = 0.348$) was used for a vehicular SSD, resulting in the below equation:

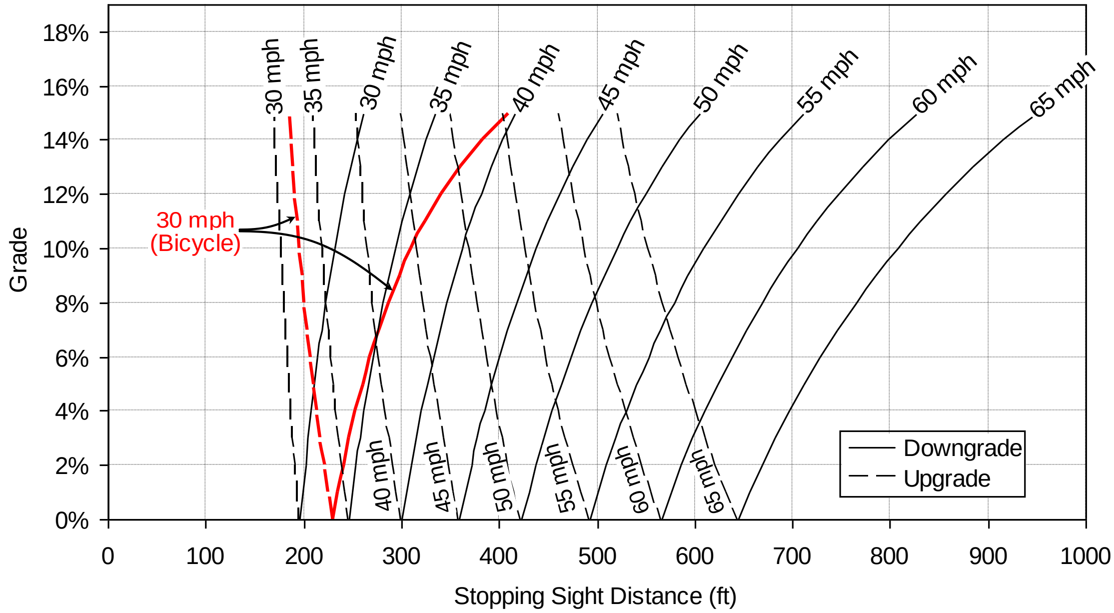
$$SSD_{Vehicles} = 1.47 \times 2.5V + \frac{V^2}{30(0.348 \pm G)} \qquad \text{Eq. (3)}$$

AASHTO's Bike Design Guide (2012) adopted the same SSD formula, Equation 2, but with a change in one parameter value for bicycles. A friction factor of 0.25 was used for bicycles (equivalently, $a = f \times g = 0.25 \times 32.2 = 8.05$ ft/s^2) to reflect a slower deceleration rate of a bicycle resulting in longer distance to stop. With the friction factor of 0.25, the SSD for bicycles can be calculated using the following equation:

$$SSD_{Bicycle} = 1.47 \times 2.5V + \frac{V^2}{30(0.250 \pm G)} \qquad \text{Eq. (4)}$$

Pein (2007) argued that the AASHTO's friction factor for bicycles (0.25) may not correctly reflect wet conditions or downgrades. Unlike motor vehicles, bicycles may be considerably affected by wet conditions or downgrades, meaning that a SSD calculated with Eq. (4) may not reflect distance that is necessary for a bicycle to stop safely. Thus, Eq. (4) should be treated with caution when it is applied to downgrades or wet conditions.

Figure 4 was created to compare SSDs calculated for bicycles and vehicles using Equations 3 and 4: VDOT's Road Design Manual (2005) present tables of SSDs for bicycles up to 30 mph. Since a slower deceleration rate is used for bicycles than that for vehicles, a SSD for bicycles is longer than that for vehicles at the same design speed. According to AASHTO's Bike Design Guide (2012), the maximum design speed for bicycles is 30 mph for shared use paths (the only design speed provided in the AASHTO's Bike Design Guide). It was reported that a typical bicyclist travels at about 14 mph (Taylor, 1993), and a strong bicyclist may sustain 25 mph on level ground (0% grade) (Pein, 2007). However, on a modest downgrade segment, bicycle speed can exceed 30 mph. Speeds of road bicycles weighing 110 lbs, 150 lbs, and 180 lbs were predicted to be over 30 mph at 4 percent downgrade with a modest pedaling power output of 100 watts (Pein, 2007). However, it should be noted that the design speed on most controlled access highways are 45 mph or more, giving more available SSD. Only 7% of the segments in the study data had speeds less than 45 mph.



- A brake reaction time of 2.5 seconds is used as in AASHTO's Green Book (2011).
- For vehicles, a friction factor of 0.348 (equivalently, a deceleration rate of 11.2 ft/s^2 is used as in AASHTO's Green Book (2011).
- For bicycles, a friction factor of 0.25 is used as in AASHTO's Bike Design Guide (2012).
- For bicycles, a maximum design speed of 30 mph for shared use paths found in ASHTO's Bike Design Guide (2012) is used.

Figure 4. Stopping sight distances for vehicles and bicycles by varying design speeds and grades.

On an upgrade segment, a bicycle's speed is expected to be reduced significantly as grade increases. Hein (1999) illustrated that speeds of two example bicycles on a 10 percent upgrade are only about one fourth of their speeds at level ground. Therefore, on an upgrade segment, a SSD for bicycles should not be a concern as long as the segment is constructed with a SSD adequate for vehicles. For a level segment designed for 35 mph or higher, the vehicular SSD is longer than the SSD for bicycles, meaning a SSD for bicycles should not be a problem as long as the segment is constructed with a SSD adequate for vehicles.

Analysis of Surrogate Crash Measures

Ideally, bicycle-vehicle crashes on shoulders would be used as a direct indicator of the safety of bicycles on shoulders of highways. However, bicycle-vehicle crashes are rare events on controlled access highways and with such a small number of crashes, it is not possible to perform a statistically reliable assessment of potential risks to bicyclists on shoulders. The small number of reported crashes does not necessarily mean that all segments are safe for bicycle use and thus, it was imperative to find a way to analyze bicyclist safety in other ways.

For this study, run-off-right crashes were selected as a surrogate crash measure since they were deemed to be the most immediate threats to bicyclists on shoulders. This does not necessarily mean vehicles in run-off-right crashes are likely to collide with bicyclists on shoulders but it does mean that segments experiencing more run-off-right crashes are expected to pose higher risks to bicyclists traveling on shoulders than those experiencing less run-off-right crashes.

Data Preparation

VDOT's Highway Traffic Records Inventory System (HTRIS) is the main source of data for the analyses conducted for this study. Three subsystems in particular, Roadway Inventory (RDI), Accident (ACC), and Highway Performance Monitoring (HPM), were used to form the initial database for this study. A set of Structure Query Language (SQL) codes was developed to relate the subsystems, and to retrieve and compile data in a compatible format for statistical analysis. Shoulder width data (SHD), a key data element for this analysis, is not available within HTRIS, yet it is collected and maintained by the Maintenance Division of VDOT. The shoulder width data is available for all segments of primary highways but for only a portion (e.g., 20-30 percent) of secondary highways. As a result, this analysis was limited to primary highways. Only paved right shoulders with either asphalt (bituminous concrete) or concrete (Portland cement concrete) pavement were considered for this study.

There were over 8,000 centerline miles of primary highways under VDOT's administration as of September, 2009. From this total, 320 miles of controlled access highways were identified for which data are available and bicycle permission/prohibition is known. Among those 320 miles, 133 miles have bicycle prohibitions in place and 187 miles do not. Only segments for which valid information exists for all variables were included in the data analysis, including traffic crash frequencies (e.g., total crash, run-off-right crash, and bicycle-vehicle crash), segment length, number of intersections in a segment, shoulder width, speed limit, and AADT. A total of 137 segments out of the 960 segments comprising the 320 mile dataset were removed due to incomplete data resulting in 823 segments over 268 miles available for data analysis. The final study database breaks down to 119 miles with bicycle prohibitions in place and 149 miles without prohibitions. See Appendix D for details on data preparation.

Characteristics of the Controlled Access Primary Highway Segments

Tables 3 and 4 summarize the basic characteristics of the 823 segments on the controlled access primary highways in Virginia. These characteristics were selected for analysis based on the study design, data availability, and the review of literature including FHWA's Bike Design Guide (1994b). FHWA's Bike Design Guide adopted five characteristics important in the selection of bicycle design treatments. These characteristics are traffic volume, average vehicle

Table 3. Basic Statistics of Segment Characteristics

Variable	Num. of obs.	Mean	Std. dev	Min	Max
AADT[1] (1,000 vehicles per day)	823	28.19	19.35	2.094	98.86
Length[2] (mile)		0.326	0.537	0.010	4.650
Curb and gutter[2,5] (1 if present; 0 if not)		0.129	0.335	0	1
Prohibit[3] (1 if prohibited; 0 if not)		0.313	0.464	0	1
Number of intersections[2]		0.644	0.773	0	2
Number of lanes[2]		4.299	0.842	2	7
Speed limit[2] (miles per hour)		53.89	8.551	35	65
Shoulder width[4] (ft)		5.055	4.197	0	14

[1]2008 HPM database

[2]2008 RDI database
[3]2008 BPP database
[4]Weighted average of right and left shoulder widths (only hard shoulders with asphalt or concrete pavement)

Table 4. Number of Segments by Number of Lanes, Speed Limit, and Access Control Type

Variable	Num. of lanes						Speed limit (mph)							Access control	
	2	**3**	**4**	**5**	**6**	**7**	**35**	**40**	**45**	**50**	**55**	**60**	**65**	**Partial**	**Full**
Num. of segments	18	7	645	25	120	8	47	13	196	6	291	98	172	322	501
Percentage (%)	2	1	78	3	15	1	6	2	24	1	35	12	21	39	61

operating speed, heavy-vehicle volume, on-street parking, and sight distance. While this study does not address the design of bicycle facilities, the same characteristics are important when deciding whether to permit bicyclists on an existing facility.

All of the segments included in the analysis are on divided primary highways. The average daily traffic across all the segments is approximately 28,000 vehicles. On about 31 percent of the segments, bicyclists were prohibited from using the shoulders. About 13 percent of the segments have a curb and gutter, which was used to define an urban section in FHWA's Bike Design Guide (1994b). The average shoulder width is about 5 feet, and a majority of the segments (78 percent) have four lanes. In terms of access control types, 322 segments (39 percent) have partial control of access and 501 segments (61 percent) have full control of access.

When the characteristics were summarized by prohibition status, some interesting findings were noted (see Appendix E for tables by prohibition status). About 95 percent of the prohibited segments have full access control whereas about 61 percent of the permitted segments have full access control. In general, the permitted segments carry more traffic and have a shorter length, a higher proportion of the presence of curb and gutter, more intersections, lower speed limits, and narrower shoulders than the prohibited segments. Since a segment with a shorter length, more traffic and/or more intersections is typically expected to experience more crashes all other conditions being the same, permitted segments are expected to experience more crashes than their prohibited counterparts. However, since prohibited segments are expected to observe higher traveling speeds due to higher speed limits, more severe consequences are expected once crashes occur than their permitted counterparts all other factors being the same. It should be noted that it is not known what factors were considered when the prohibitions on these segments were enacted. It would be inappropriate to assume that the characteristics of permitted segments are indicative of higher levels of safety than those on segments currently designated prohibited.

When determining the lowest speed that should be addressed by this guide, it is important to note that only about 7% of the segments (60 out of 823) have speed limits below 45 mph. As a result, the guide addresses highways at speed limits of 45 mph or greater.

3-Year Crash Characteristics

Tables 5 and 6 present crash statistics of the 823 segments for 3 years (2005-2007). Six different types of crashes were summarized and they were defined using a combination of information found on police crash reports such as lighting condition and vehicle maneuver. Run-off-right crashes are crashes involving vehicles that ran off a road on the right side while off-travel-lane vehicle crashes are crashes involving vehicles that might have been unable to maintain their traveling lane before or after crashes, which includes run-off right or left crashes. Nighttime crashes were those with a lighting condition on police crash reports recorded as "DARKNESS."

Table 5. 3-Year Crash Frequency per Segment on Controlled Access Primary Highways (2005-2007)

Crash type	Mean	Std. dev.	Min	Max
All crash	6.959	10.30	1	107
Run-off-right crash	0.614	1.350	0	15
Single-vehicle crash	2.169	3.359	0	34
Off-travel-lane crash	1.725	2.808	0	30
Nighttime crash	2.058	3.087	0	30
Bicycle-vehicle crash	0.004	0.060	0	1

Note: Number of observations = 823 segments

Table 6. Number of Segments on Controlled Access Primary Highways by Crash Frequency (2005-2007)

Crash type	Number of crashes per segment in 3 years					
	0	**1**	**2**	**3**	**4**	**5 +**
All crash	0	191	126	105	78	323
Run-off-right crash	563	153	56	24	6	21
Single-vehicle crash	241	240	128	79	32	103
Off-travel-lane crash	299	233	125	57	36	73
Nighttime crash	268	240	113	60	30	112
Bicycle-vehicle crash	820	3	0	0	0	0

Note: Number of observations = 823 segments

It was discovered that none of the 823 segments of partially or fully controlled access primary highways in Virginia was crash-free and each segment experienced about 7 crashes on average for the 3 years. A majority of crashes were single-vehicle crashes (about 30 percent) or occurred during no-daylight conditions including dawn, dusk and nighttime hours (about 36 percent).

Bicycle collisions with motor vehicles were very rare. According to Table 6, only 3 segments out of the 823 experienced a bicycle-vehicle crash reported to the police during the 3 years. These statistics indicate that bicycles were rarely involved with reported traffic crashes on the 268 centerline miles of primary highways for the 3 years. A study in Arizona (Moeur and Bina, 2002) also reported a low number of bicycle-involved crashes on controlled access highways including interstate highways in Arizona. Over an 11 year period (from 1999 through June 2002), there were 13 bicycle-motor vehicle crashes reported on such highways. As of 2002, Arizona permitted bicycle use on approximately 2,000 shoulder miles of controlled access highways but it should be noted that most of those are rural facilities.

Individual crash records were extracted for detailed reviews for the 3 bicycle-vehicle crashes found in the 3-year study data. One occurred on a prohibited segment with a 4-foot right shoulder, one occurred on a prohibited segment with no shoulder, and one occurred on a permitted segment with an 8-foot shoulder. None of the crashes involved alcohol or drugs and all 3 crashes were reported to be due to inattention or error of a driver or a bicyclist. All 3 crashes occurred on straight and level segments with full access control and none occurred in work zones. All 3 crashes occurred in clear weather and on a dry surface, 2 occurred in dark without street lights, and 1 occurred at dawn.

Crash Prediction Models

In order to examine effects of factors that impact the safety of bicyclists on the right shoulders, a regression method was selected. Regression was deemed appropriate because of the need to take several factors into account simultaneously. Among the crash types analyzed, the "run-off-right" crashes would be the most immediate threats to bicyclists on the right shoulders. Therefore, they appear to be the best surrogate safety measure for evaluating crash risk of bicyclists on the shoulders. In addition, three other crash types were also analyzed, all crash, off-travel-lane crash, and single-vehicle crash types and off-travel-lane and single-vehicle crashes could potentially lead to run-off-right crashes.

For each of the four crash types, a regression model was developed to relate the 3-year crash frequencies to a set of characteristics of the segments, shown in Table 3. Due to the non-negative, skewed-distributed, and over-dispersed nature of crash frequencies, a negative binomial (NB) regression model (see Cameron and Trivedi [1986] for details), which is the most frequently employed model for crash data analysis, was used to develop crash prediction models. A generalized additive model (GAM) (see Hastie and Tibshirani [1990] for details) was applied to provide guidance on appropriate functional forms for the continuous explanatory variables of the models (e.g., AADT and shoulder width). Appendix B provides descriptions of GAM and samples of GAM graphical outputs suggesting candidate functional forms. Once appropriate functional forms were determined, a final crash prediction model was developed primarily to examine potential effects of the characteristics of the segments on crash frequency. This model was then used to determine what factors are associated with potential safety risk of bicyclists on the right shoulders, which are then used to develop the guide.

The final model for the run-off-right crashes is presented in Equation 5. All the parameter estimates are statistically significant at 0.05 level and most of them are significant at 0.01 level. The final models were also developed for the other three crash types (see Appendix F) and AADT and shoulder width turned out to be influential for all the crash types. Interestingly, for all the crash types except the "all crash", the urban/rural classification showed no statistically significant influence on the number of crashes, meaning there is no difference between urban and rural segments in occurrence of the run-off-right, off-travel-lane, or single-vehicle crashes as long as AADT, shoulder widths and prohibition status are the same.

$$
\begin{aligned}
&\mathit{Run\,Off\;\;Right\;Crashes\,in\;3Years} = \\
&(\mathit{Segment\;Length}) \times \exp\begin{pmatrix}
-0.252 + 0.370(\mathit{Prohibited}) \\
+0.195(\mathit{AADT}/1{,}000) - 0.003(\mathit{AADT}/1{,}000)^2 \\
+0.348(\mathit{AADT} < 20{,}000)(\mathit{AADT}/1000) \\
-0.019(\mathit{AADT} < 20{,}000)(\mathit{AADT}/1000)^2 \\
+0.246(\mathit{AADT} > 50{,}000)((\mathit{AADT} - 50{,}000)/1000)^2 \\
+0.235(\mathit{Shoulder\;Width}) \\
-0.041(\mathit{Shoulder\;Width})(\mathit{AADT} < 20{,}000)(\mathit{AADT}/1000) \\
+0.002(\mathit{Shoulder\;Width})(\mathit{AADT} < 20{,}000)(\mathit{AADT}/1000)^2 \\
-0.017(\mathit{Shoulder\;Width})^2
\end{pmatrix} \quad \text{Eq. (5)}
\end{aligned}
$$

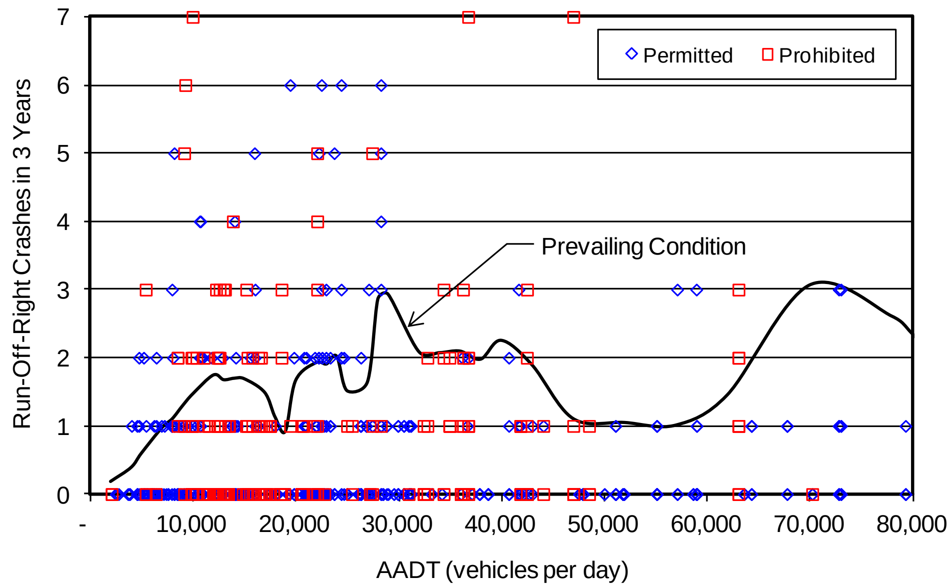
Note: shoulder width = average of widths of right shoulders with asphalt or concrete pavement

The dispersion-based goodness of fit measure (R_α^2) of the above model was calculated to be 0.33. The value (0.33) means that 33 percents of the total dispersion in the data are explained by the variables included in Equation 1. The dispersion-based measure was proposed by Miaou (1996) and is expressed as following:

$$R_k^2 = 1 - \frac{k_1}{k_0}$$

where k_1 = dispersion parameter of the final NB model; and
k_0 = dispersion parameter of the intercept-only NB model.

Since the crash prediction model presented in a mathematical form, Equation 5, might not be straightforward to understand, Figure 5 was created for easier interpretation. The figure was created by entering continuous values of AADT ranging from 2,000 to 80,000 and prevailing conditions (i.e., average values) in the four characteristics corresponding to varying levels of AADT into Equation 5. For instance, for the segments with AADTs ranging from 20,000 to 22,500, average values of prohibition, segment length, and shoulder widths of those segments were 0.297, 0.338 miles, and 5.646 feet, respectively. These values and AADT of 20,000 were entered into Equation 5, producing the expected number of crashes of 1.79.



Note: the solid curve indicates the expected number of run-off-right crashes corresponding to prevailing conditions in the data and the diamond and square symbols indicate the actual numbers.

Figure 5. Predicted numbers of run-off-right crashes with prevailing conditions on controlled access primary highways in Virginia.

In general, the predicted numbers of the crashes increase until about 12,000 in AADT and stay at about the same level until AADT reaches about 17,000. The predicted number reaches 3 crashes at around 30,000 in AADT and stay at around 2 crashes until about 40,000 in AADT. After 40,000 in AADT, the predicted numbers decrease and stay at 1 crash and start increasing again at about 60,000. Although several factors were controlled in the crash prediction model, there are factors that would be influential yet were not included in the analysis and those factors are believed to play an important role in changes in the predicted numbers over the range of AADTs.

As AADT increases, the predicted risk of run-off-right crashes, potential threat for bicyclists on the right shoulders, changes but in a non-uniform fashion possibly due to the influential factors omitted from the analysis. The AADT categories of Tables 1 and 2 (i.e., <2,000, 2,000–10,000, >10,000<) are found to be not well matched with AADTs corresponding to changes in the crash prediction curve in Figure 5. For example, the crash prediction curves predicts an increase in the risk from about 2,000 AADT until about 17,000 well past 10,000, the dividing point between the second and third categories of the tables. Although the AADT categories of the tables are not well aligned with the crash prediction curve of Virginia, it is difficult to propose new AADT categories with cut-off values driven from Figure 5. Moreover, the prediction curve is based on surrogate safety measures, run-off-right crashes, making a direct comparison difficult.

Based on the above results and discussions regarding effects of geometric and traffic characteristics of controlled access primary highways on surrogate crashes, the following summary of findings were drawn. To the extent that run-off-right crashes are an indicator of risk to bicycles on right shoulders, these findings would serve to inform decisions regarding the appropriateness of bicycle use of shoulders.

- Urban/rural classification of a highway does not affect the frequency of run-off-right, single-vehicle, or off-travel-lane crashes.

- The posted speed limit, the number of intersections, and the number of lanes do not affect the frequency of run-off-right crashes.

- A wider shoulder is generally associated with a lower number of run-off-right crashes.

Development of Guide for Permitting Bicycle Use of Right Shoulders

The findings from three approaches in the previous section were used to develop the guide: (1) review of relevant publications, (2) analysis of stopping sight distance, and (3) analysis of surrogate crash measures. This section provides an overview of the process of developing the guide (The guide is presented in Appendix G). FHWA's Bike Design Guide (1994b) provides the initial tables of minimum shoulder widths, and width modifications to those tables were made to reflect characteristics of controlled access highways in Virginia. Nine steps incorporating the modifications and engineering judgment were established to develop the final table of minimum shoulder widths and are presented in Appendix C. Other considerations for applying the table in practice were noted.

Initial Tables of Minimum Shoulder Widths for the Guide

FHWA's Bike Design Guide (1994b) serves as a starting point to develop the table of minimum shoulder widths for bicycles and as discussed earlier, a Group A bicyclist was selected as the determining bicyclist for the guide. Thus, Tables 1 and 2 are the initial tables of the minimum shoulder widths, which in the case of this guide, refer to paved right shoulders only.

Modifications to the Initial Tables

The five criteria associated with the initial tables of minimum shoulder widths were further revised based on findings from the literature review and the analyses.

Urban/Rural Classification

The final crash prediction models for the run-off-right, single-vehicle, and off-travel-lane crash types concluded that there is no difference between rural and urban segments in terms of a predicted risk of occurrence of such crashes. Given that the primary distinction between rural and urban sections with respect to bicycle use is the allowance for a wide curb lane in place of a shoulder and that the focus of this guide is on controlled access facilities, it is believed that the distinction is unnecessary. Based on these findings, the following modification is recommended regarding the rural/urban criteria:

Proposed modification: make no distinction.

Average Motor Vehicle Operating Speed

Because average motor vehicle operating speeds were not available in the study data, posted speed limits were used as a proxy in the crash prediction model. The final crash prediction model of run-off-right crashes, Equation 5, concluded that the posted speed limit does not affect the frequency of such crashes when AADT and shoulder width are taken into account. However, removal of the speed criteria from the guide is not recommended, mainly because speed is closely related to injury severity when a vehicle collides with a bicyclist. Speed is also a factor in wind force, known to be potentially problematic for bicycles on shoulders.

When evaluating existing highways, if the average operating speed for the segment in question is believed to be higher than a posted speed limit, it is recommended that speed data be collected. When considering the speed categories to address, it was noted that speed limits below 45 mph are not typical of a controlled access highway (only 7% of the study segments) and that secondly Group A bicyclists are comfortable riding in traffic at typical urban speeds. Based on the above findings and speculations, the following modifications are recommended regarding the speed criteria:

Proposed modification 1: replace table heading labeled "Average motor vehicle operating speed" with "Posted speed limit" and add a note stating "An average operating speed based on actual speed data should be used instead if there is evidence that the operating speed is higher than the posted speed limit."

Proposed modification 2: eliminate speed categories below 45 mph.

Traffic Volume

Although some difference was noted between AADTs corresponding to changes in the predicted risks of run-off-right crashes (Figure 5) and the cut-off AADTs in the tables provided in FHWA's Bike Design Guide (1994b), no recommendation for change can be supported. The use of surrogate measures makes a direct comparison difficult. As a result, no modification to the volume thresholds is recommended.

Proposed modification: none.

Sight Distance

Stopping sight distance (SSD) for bicycles was evaluated in this study. On an upgrade or level segment, the SSD for bicycles is adequate as long as the segment is constructed with the SSD adequate for motor vehicles. On a downgrade segment, a SSD for bicycles should be examined to verify that it is lower than a design SSD for vehicles by a sufficient margin when a vehicular design speed is below 40 mph. Given that speed categories below 45 mph are removed for this guide, all SSD adequate for vehicles on the highways are also adequate for bicycles. Based on these findings, the following modification is recommended regarding the sight distance criteria:

Proposed modification: replace table heading labeled sight distance requirements with stopping sight distance.

Pavement, Structural and Operational Conditions

The shoulder permitted for bicyclists should be safe for bicycle operations in terms of pavement, structures, and operations of the shoulder. Thus, the followings are recommended for inclusion in the guide:

The entire shoulder surface shall be smooth paved with a texture equal to or better than the adjacent lane for motor vehicle travel.

Drainage grates and structures on the shoulders shall be acceptable for bicycle operations or adequate space shall be available for a bicyclist to safely go around these features.

The shoulder shall not be used as a travel lane by motor vehicles at any time (e.g., peak period use of the shoulder as a travel lane or a bus bypass shoulder).

All the above modifications were incorporated in developing the final guide and the nine steps leading to the final minimum shoulder widths are presented in Appendix C. It is worth noting that two volume categories ($2{,}000 \leq AADT < 10{,}000$ and $10{,}000 \leq AADT$) were combined since minimum widths ended up being identical at the end of the nine-step process. It should also be noted that the data used in this study did not include segments of the secondary highways. Thus, all the above modifications should be reexamined when the shoulder width data for a majority of segments on the secondary highways are collected and the analysis for those segments is completed. Table 7 presents the final minimum widths of paved right shoulders for the guide and the steps leading to the table are found in Appendix C.

Table 7. Minimum Widths of Right Shoulder for Bicycle Use

Posted speed limit*	Average annual daily traffic volume (AADT) (vehicles per day)	
	<2,000	≥2,000
45 mph	3 ft	4 ft
50 mph	4.5 ft	
55 mph	5.5 ft	
60 mph	6.5 ft	
65 mph	7 ft	

*An average operating speed based on actual speed data should be used instead if there is evidence that the operating speed is higher than the posted speed limit.

Other Considerations

Factors other than those discussed above need to be taken into account when considering the appropriateness of allowing bicycle use of shoulders. Specifically, three considerations are noted here: (1) Protecting Existing Permission Not Satisfying the Proposed Minimum Widths, (2) Civil Rights Considerations, and (3) Existing Safety Conditions.

Protecting Existing Permission Not Satisfying the Proposed Minimum Widths

It is possible that a segment that currently permits bicycle use of right shoulders would not satisfy the minimum shoulder widths or the other conditions provided in this guide. Thus, the following is recommended for inclusion in the guide:

> *When it is determined that a highway segment currently permitting access to bicyclists does not satisfy the conditions in the guide, the existing permission shall not be removed until such time when an alternate facility or route is constructed and an engineering study of the segment is conducted.*

Civil Rights Considerations

In rare situations on partially controlled roads, there is a private entrance or a private road leading to a residential home, farm or even a commercial business. These access points are typically artifacts of older facilities that could not be effectively relocated when the highways widened or upgraded. Bicycle prohibitions on highways with such access points should be carefully considered since prohibitions may violate a person's rights under the Americans with Disabilities Act (ADA). Thus, the following is recommended for inclusion in the guide:

> *When it is determined that a highway segment currently permitting access to bicyclists does not satisfy the conditions in the guide, the existing permission shall not be removed when doing so would violate a person's rights under the Americans with Disabilities Act (ADA).*

Existing Safety Conditions

In cases in which a segment meets the recommendations in the guide but still poses a risk for bicyclists, based on crash history and engineering judgment, efforts to resolve the risk should be made before prohibition of bicyclists is considered. Potential engineering treatments to resolve the risk are found in *Traffic Engineering Design Manual 2011* (VDOT, 2011). Thus, the following is recommended for inclusion in the guide:

> *If a segment satisfies the recommendations of the guide but there is a known safety issue associated with bicycle use, efforts shall first be made to resolve the safety issue through engineering treatments such as signage or geometric changes before any prohibition of bicyclists is considered. Potential treatments are listed in the VDOT's Traffic Engineering Design Manual.*

CONCLUSIONS

Two conclusions were drawn from analysis results as follows:

- *Bicycle use of controlled access facilities in Virginia appears to be safe based on available crash data*. Data show few crashes involving bicyclists using the controlled access facilities. However, an underreporting of bicycle crashes may exist and the volume of bicycle use of controlled access highways in Virginia is unknown.

- *Traffic volume and shoulder width would affect the potential occurrence of bicycle-vehicle crashes on the right shoulders of the controlled access facilities while urban/rural classification, speed limit, and the number of intersections would not in Virginia*. Based on an empirical analysis of "run-off-right" crash data, used as a surrogate for bicycle crashes on the right shoulders, the data indicate that urban/rural classification, the posted speed limit, and the number of intersections do not affect the frequency of "run-off-right" crashes when AADT and shoulder width are taken into account.

RECOMMENDATIONS

- *VDOT TMPD should use the proposed guide when making recommendations regarding permission and prohibition of bicycle use of right shoulders on segments of controlled access highways.* The Guide was based on AASHTO's Bike Design Guide (2012), FHWA's Bike Design Guide (1994b), VDOT's Guidelines, the state of the practice, theoretical analysis of stopping sight distance, and an empirical analysis of crash, traffic, and geometric data. Thus, the guide is considered to be reliable and valid. However, the guide should not serve as a warrant or requirement.

BENEFITS AND IMPLEMENTATION PROSPECTS

The CTB Bicycle/Pedestrian Policy Implementation Team is an interdisciplinary group that was directed by the former Secretary of Transportation and the former VDOT Commissioner to develop guidance on bicycle use of controlled access facilities. The members of this team are the champions of this project. They have been integrally involved in the study and have approved the work.

Since the proposed guide represents the state of the practice, the guidelines approved by AASHTO, FHWA and VDOT, and the results of empirical research, it should be immediately useful to VDOT personnel making recommendations regarding permission or prohibition to the CTB, including the state bicycle and pedestrian coordinator. It is up to the Bicycle/Pedestrian Policy Implementation Team whether they will further propose that the CTB adopt the guide as well.

ACKNOWLEDGMENTS

This project could not have been completed without the help of the nine VDOT districts providing bicycle prohibition data; CO Maintenance Division providing shoulder width data; In-Kyu Lim (CO TED) providing assistance in merging datasets; Marsha Fiol (CO TMPD) arranging data collection for bicycle prohibition status; the project Technical Review Panel (Jim Gillespie, John Bolecek, George Rogerson, and Ben Cottrell) providing guidance and suggestions throughout the project; JoAnne Maxwell and Holly Jones (CO Policy Division) offering comments and suggestions for the report; Cheryl Lynn, Ken Lantz, and Wayne Ferguson (all formerly VCTIR) contributing to the study before retirement; and Linda Evans (VCTIR) providing professional editorial help on the report. The author is truly grateful for their assistance.

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APPENDIX A.
Commonwealth Transportation Board
Policy for Integrating Bicycles and Pedestrian Accommodations

Policy for Integrating Bicycles and Pedestrian Accommodations
Approved: 3/18/2004

1. Introduction

Bicycling and walking are fundamental travel modes and integral components of an efficient transportation network. Appropriate bicycle and pedestrian accommodations provide the public, including the disabled community, with access to the transportation network; connectivity with other modes of transportation; and independent mobility regardless of age, physical constraints, or income. Effective bicycle and pedestrian accommodations enhance the quality of life and health, strengthen communities, increase safety for all highway users, reduce congestion, and can benefit the environment. Bicycling and walking are successfully accommodated when travel by these modes is efficient, safe, and comfortable for the public. A strategic approach will consistently incorporate the consideration and provision of bicycling and walking accommodations into the decision-making process for Virginia's transportation network.

2. Purpose

This policy provides the framework through which the Virginia Department of Transportation 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.

For the purposes of this policy, an accommodation is defined as any facility, design feature, operational change, or maintenance activity that improves the environment in which bicyclists and pedestrians travel. Examples of such accommodations include the provision of bike lanes, sidewalks, and signs; the installation of curb extensions for traffic calming; and the addition of paved shoulders.

3. Project Development

The Virginia Department of Transportation (VDOT) will initiate all highway construction projects with the presumption that the projects shall accommodate bicycling and walking. Factors that support the need to provide bicycle and pedestrian accommodations include, but are not limited to, the following:

- project is identified in an adopted transportation or related plan
- project accommodates existing and future bicycle and pedestrian use
- project improves or maintains safety for all users
- project provides a connection to public transportation services and facilities
- project serves areas or population groups with limited transportation options
- project provides a connection to bicycling and walking trip generators such as employment,
- education, retail, recreation, and residential centers and public facilities
- project is identified in a Safe Routes to School program or provides a connection to a school
- project provides a regional connection or is of regional or state significance
- project provides a link to other bicycle and pedestrian accommodations
- project provides a connection to traverse natural or man-made barriers

- project provides a tourism or economic development opportunity

Project development for bicycle and pedestrian accommodations will follow VDOT's project programming and scheduling process and concurrent engineering process. VDOT will encourage the participation of localities in concurrent engineering activities that guide the project development.

3.1 Accommodations Built as Independent Construction Projects

Bicycle and pedestrian accommodations can be developed through projects that are independent of highway construction, either within the highway right-of-way or on an independent right-of-way. Independent construction projects can be utilized to retrofit accommodations along existing roadways, improve existing accommodations to better serve users, and install facilities to provide continuity and accessibility within the bicycle and pedestrian network. These projects will follow the same procedures as those for other construction projects for planning, funding, design, and construction. Localities and metropolitan planning organizations will be instrumental in identifying and prioritizing these independent construction projects.

3.2 Access-Controlled Corridors

Access-controlled corridors can create barriers to bicycle and pedestrian travel. Bicycling and walking may be accommodated within or adjacent to access-controlled corridors through the provision of facilities on parallel roadways or physically separated parallel facilities within the right-of-way. Crossings of such corridors must be provided to establish or maintain connectivity of bicycle and pedestrian accommodations.

3.3 Additional Improvement Opportunities

Bicycle and pedestrian accommodations will be considered in other types of projects. Non-construction activities can be used to improve accommodations for bicycling and walking. In addition, any project that affects or could affect the usability of an existing bicycle or pedestrian accommodation within the highway system must be consistent with state and federal laws.

3.3.1 Operation and Maintenance Activities

Bicycling and walking should be considered in operational improvements, including hazard elimination projects and signal installation. Independent operational improvements for bicycling and walking, such as the installation of pedestrian signals, should be coordinated with local transportation and safety offices. The maintenance program will consider bicycling and walking so that completed activities will not hinder the movement of those choosing to use these travel modes. The maintenance program may produce facility changes that will enhance the environment for bicycling and walking, such as the addition of paved shoulders.

3.3.2 Long Distance Bicycle Routes

Long distance bicycle routes facilitate travel for bicyclists through the use of shared lanes, bike lanes, and shared use paths, as well as signage. All projects along a long distance route meeting the criteria for an American Association of State Highway and Transportation Officials (AASHTO) or *Manual on Uniform Traffic Control Devices* (MUTCD) approved numbered bicycle route system should provide the necessary design features to facilitate bicycle travel. Independent construction projects and other activities can be utilized to make improvements for existing numbered bicycle routes. Consideration should be given to facilitating the development of other types of long distance routes.

3.3.3 Tourism and Economic Development

Bicycling and walking accommodations can serve as unique transportation links between historic, cultural, scenic, and recreational sites, providing support to tourism activities and resulting economic development. Projects along existing or planned tourism and recreation corridors should include bicycle and pedestrian accommodations. In addition, the development of independent projects to serve this type of tourism and economic development function should be considered and coordinated with economic development organizations at local, regional, and state levels, as well as with other related agencies. Projects must also address the need to provide safety and connectivity for existing and planned recreational trails, such as the Appalachian Trail, that intersect with the state's highway system.

3.4 Exceptions to the Provision of Accommodations

Bicycle and pedestrian accommodations should be provided except where one or more of the following conditions exist:

- scarcity of population, travel, and attractors, both existing and future, indicate an absence of need for such accommodations
- environmental or social impacts outweigh the need for these accommodations
- safety would be compromised
- total cost of bicycle and pedestrian accommodations to the appropriate system (i.e., interstate, primary, secondary, or urban system) would be excessively disproportionate to the need for the facility
- purpose and scope of the specific project do not facilitate the provision of such accommodations (e.g., projects for the Rural Rustic Road Program)
- bicycle and pedestrian travel is prohibited by state or federal laws

3.5 Decision Process

The project manager and local representatives will, based on the factors listed previously in this section, develop a recommendation on how and whether to accommodate bicyclists and pedestrians in a construction project prior to the public hearing. The district administrator should confirm this recommendation prior to the public hearing. Public involvement comments will be reviewed and incorporated into project development prior to the preparation of the design approval recommendation. When a locality is not in agreement with VDOT's position on how bicyclists and pedestrians will or will not be accommodated in a construction project, the locality can introduce a formal appeal by means of a resolution adopted by the local governing body. The resolution must be submitted to the district administrator to be reviewed and considered prior to the submission of the design approval recommendation to the chief engineer for program development. Local resolutions must be forwarded to the chief engineer for program development for consideration during the project design approval or to the Commonwealth Transportation Board for consideration during location and design approval, if needed for a project. The resolution and supporting information related to the recommendation must be included in the project documentation. The decisions made by VDOT and localities for the provision of bicycle and pedestrian travel must be consistent with state and federal laws regarding accommodations and access for bicycling and walking.

4. Discipline Participation in Project Development

VDOT will provide the leadership to implement this policy. Those involved in the planning, funding, design, construction, operation, and maintenance of the state's highways are responsible for effecting the guidance set forth in this policy. VDOT recognizes the need for interdisciplinary coordination to efficiently develop, operate, and maintain bicycle and pedestrian accommodations.

Procedures, guidelines, and best practices will be developed or revised to implement the provisions set forth in this policy. For example, objective criteria will be prepared to guide decisions on the restriction of bicycle and pedestrian use of access-controlled facilities. VDOT will work with localities, regional planning agencies, advisory committees, and other stakeholders to facilitate implementation and will offer training or other resource tools on planning, designing, operating, and maintaining bicycle and pedestrian accommodations.

4.1 Planning

VDOT will promote the inclusion of bicycle and pedestrian accommodations in transportation planning activities at local, regional, and statewide levels. These planning activities include, but are not limited to, corridor studies, small urban studies, regional plans, and the statewide multimodal long-range transportation plan. To carry out this task, VDOT will coordinate with local government agencies, regional planning agencies, and community stakeholder groups. In addition, VDOT will coordinate with the Virginia Department of Rail and Public Transportation (VDRPT) and local and regional transit providers to identify needs for bicycle and pedestrian access to public transportation services and facilities.

4.2 Funding

Highway construction funds can be used to build bicycle and pedestrian accommodations either concurrently with highway construction projects or as independent transportation projects. Both types of bicycle and pedestrian accommodation projects will be funded in the same manner as other highway construction projects for each system (i.e., interstate, primary, secondary, or urban). VDOT's participation in the development and construction of an independent project that is not associated with the interstate, primary, secondary, or urban systems will be determined through a negotiated agreement with the locality or localities involved.

Other state and federal funding sources eligible for the development of bicycle and pedestrian accommodations may be used, following program requirements established for these sources. These sources include, but are not limited to, programs for highway safety, enhancement, air quality, congestion relief, and special access.

VDOT may enter into agreements with localities or other entities in order to pursue alternate funding to develop bicycle and pedestrian accommodations, so long as the agreements are consistent with state and federal laws.

4.3 Design and Construction

VDOT will work with localities to select and design accommodations, taking into consideration community needs, safety, and unique environmental and aesthetic characteristics as they relate to specific projects. The selection of the specific accommodations to be used for a project will be based on the application of appropriate planning, design, and engineering principles. The accommodations will be designed and built, or installed, using guidance from VDOT and AASHTO publications, the MUTCD, and the Americans with Disabilities Act Accessibility Guidelines (ADAAG). Methods for providing flexibility within safe design parameters, such as context sensitive solutions and design, will be considered.

During the preparation of an environmental impact statement (EIS), VDOT will consider the current and anticipated future use of the affected facilities by bicyclists and pedestrians, the potential impacts of the alternatives on bicycle and pedestrian travel, and proposed measures, if any, to avoid or reduce adverse impacts to the use of these facilities by bicyclists and pedestrians.

During project design VDOT will coordinate with VDRPT to address bicyclist and pedestrian access to existing and planned transit connections.

Requests for exceptions to design criteria must be submitted in accordance with VDOT's design exception review process. The approval of exceptions will be decided by the Federal Highway Administration or VDOT's Chief Engineer for Program Development.

VDOT will ensure that accommodations for bicycling and walking are built in accordance with design plans and VDOT's construction standards and specifications.

4.4 Operations

VDOT will consider methods of accommodating bicycling and walking along existing roads through operational changes, such as traffic calming and crosswalk marking, where appropriate and feasible.

VDOT will work with VDRPT and local and regional transit providers to identify the need for ancillary facilities, such as shelters and bike racks on buses, that support bicycling and walking to transit connections.

VDOT will enforce the requirements for the continuance of bicycle and pedestrian traffic in work zones, especially in areas at or leading to transit stops, and in facility replacements in accordance with the MUTCD, VDOT Work Area Protection Manual, and VDOT Land Use Permit Manual when construction, utility, or maintenance work, either by VDOT or other entities, affects bicycle and pedestrian accommodations.

VDOT will continue to research and implement technologies that could be used to improve the safety and mobility of bicyclists and pedestrians in Virginia's transportation network, such as signal detection systems for bicycles and in-pavement crosswalk lights.

4.5 Maintenance

VDOT will maintain bicycle and pedestrian accommodations as necessary to keep the accommodations usable and accessible in accordance with state and federal laws and VDOT's asset management policy. Maintenance of bike lanes and paved shoulders will include repair, replacement, and clearance of debris. As these facilities are an integral part of the pavement structure, snow and ice control will be performed on these facilities.

For sidewalks, shared use paths, and bicycle paths built within department right-of-way, built to department standards, and accepted for maintenance, VDOT will maintain these bicycle and pedestrian accommodations through replacement and repair. VDOT will not provide snow or ice removal for sidewalks and shared use paths. The execution of agreements between VDOT and localities for maintenance of such facilities shall not be precluded under this policy.

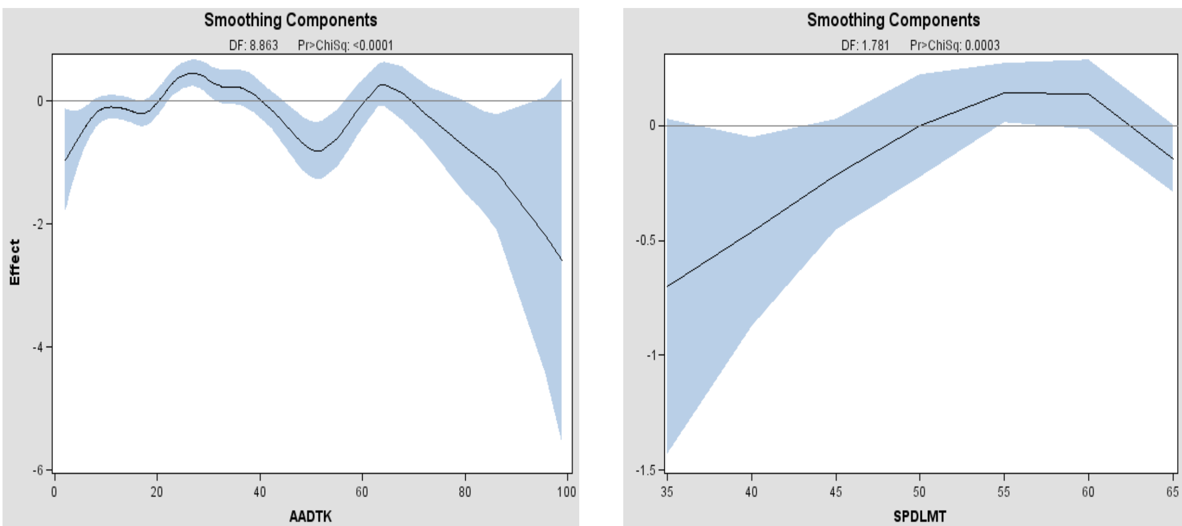
5. Effective Date

This policy becomes effect upon its adoption by the Commonwealth Transportation Board on March 18, 2004, and will apply to projects that reach the scoping phase after its adoption. This policy shall supersede all current department policies and procedures related to bicycle and pedestrian accommodations. VDOT will develop or revise procedures, guidelines, and best practices to support and implement the provisions set forth in this policy, and future departmental policies and procedural documents shall comply with the provisions set forth in this policy.

APPENDIX B.
GENERALIZED ADDITIVE MODEL GRAPHICAL RESULTS

Hastie and Tibshirani (1990) married the additive approach proposed by Stone (1985) to the generalized linear model proposed by Nelder and Wedderburn (1972) and established by McCullagh and Nelder (1989), giving a birth to the generalized additive model (GAM). GAM combines flexibility of nonparametric regression with interpretability of generalized linear regression. The main output of a GAM is a graph showing remaining effects of an explanatory variable of interest after a linear effect of the variable is removed, which is a format of SAS© software. Based on GAM graphical outputs, an appropriate functional form can be proposed.

GAM produces graphs (e.g., Figure B-1) that were used to suggest appropriate functional forms of continuous variables included in the crash prediction models. Figure B-1 shows nonparametric model curves after a linear effect of AADT in 1,000 and speed limit on the number of run-off-right crashes is removed.



(a) AADT in 1,000 **(b) Speed Limit**

Figure B-1. GAM result graph of AADT and speed limit.

APPENDIX C.
NINE STEPS OF DEVELOPING THE FINAL MINIMUM SHOUDLER WIDTHS

Considering the initial tables from FHWA's Bike Design Guide (1994b) (presented earlier as Tables 1 and 2) and the modifications addressed in the section, "Development of Guide for Permitting Bicycle Use of Right Shoulders," nine steps were laid out to create the minimum shoulder widths for determining where bicycle use is appropriate on right shoulders of controlled access facilities from a safety standpoint.

Step 1: Start with Tables for Group A Bicyclists in FHWA's Bike Design Guide

The tables for Group A bicyclists in urban sections without street parking and in rural section in FHWA's Bike Design Guide (1994b), Tables 1 and 2, were adopted as the initial width tables. Speed categories below 45 mph were removed as shown in Tables C-1 and C-2.

Table C-1. Minimum Widths of Wide Curb or Shoulder for Group A Bicyclists in Urban Section Without Street Parking (feet)

Average operating speed	Average annual daily traffic volume (AADT) (vehicles per day)											
	<2,000				2,000–10,000				>10,000			
	Stopping sight distance				Stopping sight distance				Stopping sight distance			
	Adequate		Inadequate		Adequate		Inadequate		Adequate		Inadequate	
		Truck, bus, rv				Truck, bus, rv				Truck, bus, rv		
45-50 mph	wc 15	wc 15	wc 15	wc 15	wc 15	wc 15	sh 6	sh 6	wc 15	wc 15	sh 6	sh 6
>50 mph	sh 6	sh 6	sh 6	sh 6	sh 6	sh 6	sh 6	sh 6	sh 6	sh 6	sh 6	sh 6

Note: wc=wide curb and sh=shoulder

Table C-2. Minimum Widths of a Shoulder for Group A Bicyclists in Rural Section (feet)

Average operating speed	Average annual daily traffic volume (AADT) (vehicles per day)											
	<2,000				2,000–10,000				>10,000			
	Stopping sight distance				Stopping sight distance				Stopping sight distance			
	Adequate		Inadequate		Adequate		Inadequate		Adequate		Inadequate	
		Truck, bus, rv				Truck, bus, rv				Truck, bus, rv		
45-50 mph	sh 4	sh 4	sh 4	sh 4	sh 6	sh 6	sh 6	sh 6	sh 6	sh 6	sh 6	sh 6
>50 mph	sh 4	sh 6	sh 6	sh 4	sh 6	sh 6	sh 6	sh 6	sh 6	sh 6	sh 6	sh 6

Note: sh=shoulder

Step 2: Convert Wide Curb Widths to Comparable Shoulder Widths

Table C-1 for an urban section refers to a wide curb rather than shoulder width in determining appropriate accommodations for bicycle traffic. To obtain a width of a shoulder width comparable to that of a wide curb, the following equation was applied assuming a 12-foot right lane abutting the shoulder:

comparable shoulder width = wide curb width – typical lane width (12 feet)

Comparable shoulder widths replace wide curb widths in Table B-1 resulting in Table B-3.

Table C-3. Minimum Widths of a Shoulder for Group A Bicyclists in Urban Section Without Street Parking (feet)

Average operating speed	Average annual daily traffic volume (AADT) (vehicles per day)											
	<2,000				2,000–10,000				>10,000			
	Stopping sight distance				Stopping sight distance				Stopping sight distance			
	Adequate		Inadequate		Adequate		Inadequate		Adequate		Inadequate	
		Truck, bus, rv				Truck, bus, rv				Truck, bus, rv		
45-50 mph	sh 3	sh 3	sh 3	sh 3	sh 3	sh 3	sh 6	sh 6	sh 3	sh 3	sh 6	sh 6
>50 mph	sh 6	sh 6	sh 6	sh 6	sh 6	sh 6	sh 6	sh 6	sh 6	sh 6	sh 6	sh 6

Note: sh=shoulder

Step 3: Modify Minimum Design Widths Suitable for the Guide

The following considerations are made:

- The physical width of the bicyclist is 2.5 feet (i.e., 30 inches) as seen in Figure 3-1 (AASHTO, 2011).
- Tables C-1 and C-2 (thus, also Table C-3) were developed to aid in the design of bicycle facilities while the goal of this study is to develop guidance on conditions that can permit bicycle us of right shoulders of controlled access highways. Guidance for determining the use of a facility is typically less stringent than guidance for the design of facility.
- Based on input from engineers, it was determined that a minimum shoulder width of the design value minus 2 feet was sufficient for allowing bicycle use of shoulders, with a minimum shoulder width of 2.5 feet.

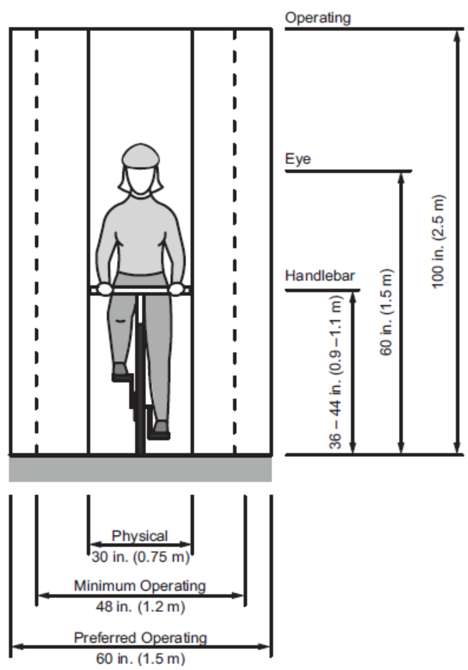


Figure C-1. Bicyclist Operating Space (Figure 3-1, AASHTO, 2012)

Following the above considerations, a modified shoulder width is calculated as follows:

modified shoulder width = max[(minimum design shoulder width–2 feet), 2.5 feet]

Table C-4. Minimum Widths of Shoulder for Group A Bicyclists in Urban Section Without Street Parking (feet)

Average operating speed	Average annual daily traffic volume (AADT) (vehicles per day)											
	<2,000				2,000–10,000				>10,000			
	Stopping sight distance				Stopping sight distance				Stopping sight distance			
	Adequate		Inadequate		Adequate		Inadequate		Adequate		Inadequate	
		Truck, bus, rv				Truck, bus, rv				Truck, bus, rv		
45-50 mph	2.5	2.5	2.5	2.5	2.5	2.5	4	4	2.5	2.5	4	4
>50 mph	4	4	4	4	4	4	4	4	4	4	4	4

Table C-5. Minimum Widths of Shoulder for Group A Bicyclists in Rural Section (feet)

Average operating speed	Average annual daily traffic volume (AADT) (vehicles per day)											
	<2,000				2,000–10,000				>10,000			
	Stopping sight distance				Stopping sight distance				Stopping sight distance			
	Adequate		Inadequate		Adequate		Inadequate		Adequate		Inadequate	
		Truck, bus, rv				Truck, bus, rv				Truck, bus, rv		
45-50 mph	2.5	2.5	2.5	2.5	4	4	4	4	4	4	4	4
>50 mph	2.5	4	4	2.5	4	4	4	4	4	4	4	4

Step 4: Compare Minimum Widths for Urban and Rural Sections and Select Larger of Two Widths

Since there was no difference between urban and rural segments in the analysis of run-off-right crashes, combining minimum widths for urban and rural sections is suggested. A larger width between the two tables is adopted for each cell to create a new table as follows:

combined shoulder width = max(width in Table C-4, width in Table C-5)

For example, for a highway segment with an AADT of less than 2,000 vehicles, adequate stopping sight distance, and average speed of over 50 mph, the minimum shoulder widths are 4 and 2.5 feet for urban (Table C-4) and rural (Table C-5) sections, respectively. Thus, a larger value, 4 feet, is adopted as the minimum width for that condition. Table C-6 is a resultant of combining the two tables.

Table C-6. Minimum Widths of Shoulder for Group A Bicyclists (feet)

Average operating speed	Average annual daily traffic volume (AADT) (vehicles per day)											
	<2,000				2,000–10,000				>10,000			
	Stopping sight distance				Stopping sight distance				Stopping sight distance			
	Adequate		Inadequate		Adequate		Inadequate		Adequate		Inadequate	
		Truck, bus, rv				Truck, bus, rv				Truck, bus, rv		
45-50 mph	2.5	2.5	2.5	2.5	4	4	4	4	4	4	4	4
>50 mph	4	4	4	4	4	4	4	4	4	4	4	4

Step 5: Calculate Minimum Shoulder Widths Maintaining Safe Separation Distance Due to Wind Force

The following conditions are considered:

- Width of a truck=8.5 feet (102 inches) (FHWA, 2004)
- Essential physical operating space of a bicyclist=3.3 feet (40 inches) (AASHTO, 2012)
- Width of the outside lane=12 feet

The following assumptions are made:

- An operating space of an 8.5-foot wide truck is 10 feet, 1 foot away from each end of a 12-foot lane.
- A bicyclist operates 1.65 feet from the edge of the pavement (1.65 feet is a half of the essential operating space [40 inches=3.3 feet] of a bicyclist [see Figure C-1]).

Safe separation distances to address wind force caused by passing trucks are found from Figure 2, Aerodynamic forces caused by heavy vehicles passing bicycles (FHWA, 1977). According to Figure 2, the safe separation distances corresponding to different speeds are found as below;

- 2.5 feet at 45 mph
- 3.75 feet at 50 mph
- 5 feet at 55 mph
- 6 feet at 60 mph
- 6.5 feet at 65 mph

Minimum shoulder widths required to maintain the above safe separation distances while considering other relevant conditions and assumptions are calculated as follow:

minimum shoulder width for safe separation = safe separation distance (A) – space between the right line of the lane and the right limit of a typical vehicle operating space (B) + space between a bicyclist and the edge of an pavement (C)

Figure B-2 presents relevant widths and spaces for shoulder width calculation based on the safe separation distance due to wind forces caused by passing trucks. The safe separation distance (A) is from Figure 2 and the width between the right line of the lane and the right edge of the operating space of a truck in the lane (B) is 1 foot based on the assumption of 10-foot operating space of a truck in a 12-foot lane. A half of the operating space of a bicyclist (C) is 1.65 feet.

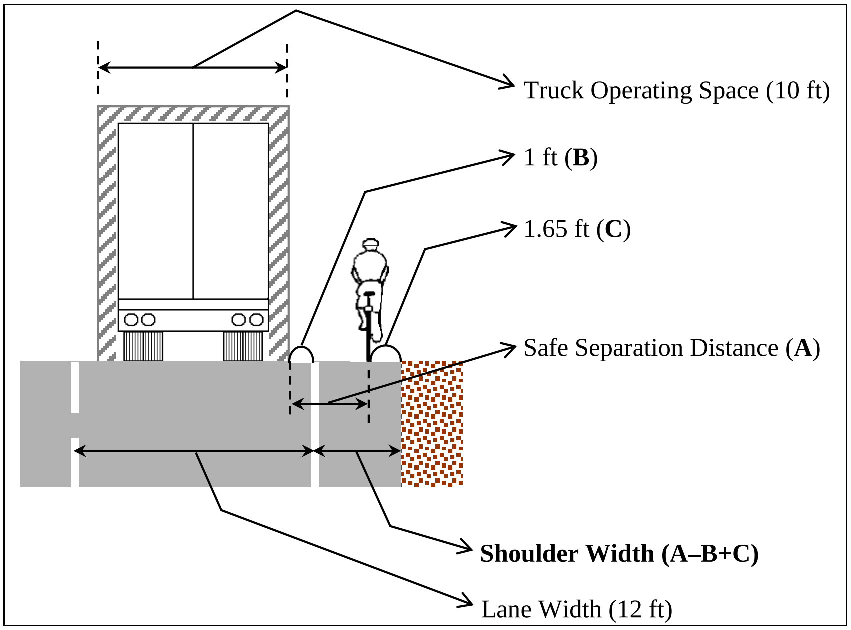


Figure C-2. Shoulder width calculation.

The calculated minimum shoulder widths for safe separation are:

- 3.15 feet (2.5'–1.0'+1.65') at 45 mph
- 4.40 feet (3.75'–1.0'+1.65') at 50 mph
- 5.65 feet (5.0'–1.0'+1.65') at 55 mph
- 6.65 feet (6.0'–1.0'+1.65') at 60 mph
- 7.15 feet (6.5'–1.0'+1.65') at 65 mph

Table C-7 presents the calculated widths in a table format consistent with tables in the FHWA's Bike Design Guide (FHWA, 1994b):

Table C-7. Minimum Widths of Shoulder for Safe Separation Due to Wind (feet)

Average operating speed	Average annual daily traffic volume (AADT) (vehicles per day)											
	<2,000				2,000–10,000				>10,000			
	Stopping sight distance				Stopping sight distance				Stopping sight distance			
	Adequate		Inadequate		Adequate		Inadequate		Adequate		Inadequate	
		Truck, bus, rv				Truck, bus, rv				Truck, bus, rv		
45 mph	3.15	3.15	3.15	3.15	3.15	3.15	3.15	3.15	3.15	3.15	3.15	3.15
46-50 mph	4.40	4.40	4.40	4.40	4.40	4.40	4.40	4.40	4.40	4.40	4.40	4.40
51-55 mph	5.65	5.65	5.65	5.65	5.65	5.65	5.65	5.65	5.65	5.65	5.65	5.65
56-60 mph	6.65	6.65	6.65	6.65	6.65	6.65	6.65	6.65	6.65	6.65	6.65	6.65
61-65 mph	7.15	7.15	7.15	7.15	7.15	7.15	7.15	7.15	7.15	7.15	7.15	7.15

Step 6: Compare Tables C-6 and C-7 Generated in Steps 4 and 5

Shoulder widths in Table C-7 are the minimum widths for stable operation of a bicycle while those in Table C-6 are the minimum widths modified from design widths. In order to satisfy all the conditions and assumptions considered through Step 5, the larger of the two values is adopted to create Table C-8 as follows:

combined shoulder width = max(width in Table C-6, width in Table C-7)

For example, for AADT of less than 2,000, adequate stopping sight distance, and average speed of 45 mph, the minimum shoulder widths are 2.5 and 3.15 feet in Tables C-6 and C-7, respectively. Thus, a larger value, 3.15 feet, is adopted as the minimum width for that condition.

Table C-8. Minimum Widths of Shoulder for Bicyclists (feet)

Average operating speed	Average annual daily traffic volume (AADT) (vehicles per day)											
	<2,000				2,000–10,000				>10,000			
	Stopping sight distance				Stopping sight distance				Stopping sight distance			
	Adequate		Inadequate		Adequate		Inadequate		Adequate		Inadequate	
		Truck, bus, rv				Truck, bus, rv				Truck, bus, rv		
45 mph	3.15	3.15	3.15	3.15	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00
46-50 mph	4.40	4.40	4.40	4.40	4.40	4.40	4.40	4.40	4.40	4.40	4.40	4.40
51-55 mph	5.65	5.65	5.65	5.65	5.65	5.65	5.65	5.65	5.65	5.65	5.65	5.65
56-60 mph	6.65	6.65	6.65	6.65	6.65	6.65	6.65	6.65	6.65	6.65	6.65	6.65
61-65 mph	7.15	7.15	7.15	7.15	7.15	7.15	7.15	7.15	7.15	7.15	7.15	7.15

Step 7: Use Posted Speed Limits

For practical use of the table, a posted speed limit is recommended for use in place of the average operating speed because operating speed data are typically unavailable for highway segments. However, when operating speeds are thought to be higher than the posted speed limit, speed data should be collected and an average operating speed should be used in place of the posted speed limit.

Table C-9. Minimum Widths of Shoulder for Bicyclists (feet)

Posted speed limit	Average annual daily traffic volume (AADT) (vehicles per day)											
	<2,000				2,000–10,000				>10,000			
	Stopping sight distance				Stopping sight distance				Stopping sight distance			
	Adequate		Inadequate		Adequate		Inadequate		Adequate		Inadequate	
		Truck, bus, rv				Truck, bus, rv				Truck, bus, rv		
45 mph	3.15	3.15	3.15	3.15	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00
50 mph	4.40	4.40	4.40	4.40	4.40	4.40	4.40	4.40	4.40	4.40	4.40	4.40
55 mph	5.65	5.65	5.65	5.65	5.65	5.65	5.65	5.65	5.65	5.65	5.65	5.65
60 mph	6.65	6.65	6.65	6.65	6.65	6.65	6.65	6.65	6.65	6.65	6.65	6.65
65 mph	7.15	7.15	7.15	7.15	7.15	7.15	7.15	7.15	7.15	7.15	7.15	7.15

Step 8: Round Values for Practical Use

For practical use of the table, values in Table C-9 are rounded so that widths are based on 0.5 feet increments. All values are rounded to the nearest 0.5 ft favoring permitting bicycle use.

Table C-10. Minimum Widths of Shoulder for Bicyclists (feet)

Posted speed limit	Average annual daily traffic volume (AADT) (vehicles per day)											
	<2,000				2,000–12,000				>12,000			
	Stopping sight distance				Stopping sight distance				Stopping sight distance			
	Adequate		Inadequate		Adequate		Inadequate		Adequate		Inadequate	
		Truck, bus, rv				Truck, bus, rv				Truck, bus, rv		
45 mph	3	3	3	3	4	4	4	4	4	4	4	4
50 mph	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5
55 mph	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5
60 mph	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5
65 mph	7	7	7	7	7	7	7	7	7	7	7	7

Step 9: Combine Two Higher Volume Categories and Remove Stopping Sight Distance and Presence of Heavy Vehicles Categories

All the widths for two higher AADT categories, 2,000-10,000 and >10,000, are identical. Thus, for simplicity, the two categories are combined so that the final table has two volume categories, <2,000 and ≥2,000. In addition, stopping sight distance and the presence of heavy vehicles are removed from the table since the widths are identical under the same speed limit.

Table C-11. Minimum Widths of Shoulder for Bicyclists

Posted speed limit	Average annual daily traffic volume (AADT) (vehicles per day)	
	<2,000	≥2,000
45 mph	3 ft	4 ft
50 mph	4.5 ft	
55 mph	5.5 ft	
60 mph	6.5 ft	
65 mph	7 ft	

APPENDIX D.
DATA PREPARATION FOR CRASH ANALYSIS

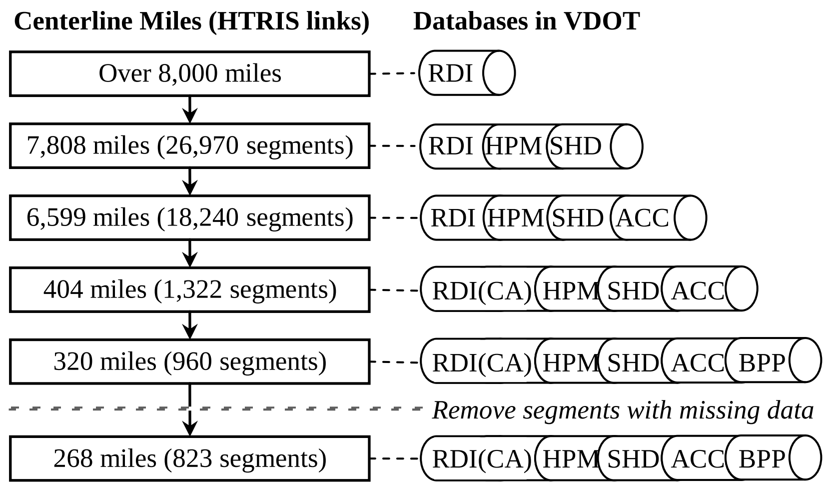
VDOT maintains detailed data on the historical roadway inventory, traffic flows, and traffic crashes in the Highway Traffic Records Inventory System (HTRIS), which serves as a centralized warehouse of traffic and roadway inventory data in Virginia. HTRIS is operated in a relational Oracle database and consists of several subsystems storing unique data on each subsystem. The three subsystems, Roadway Inventory (RDI), Accident (ACC), and Highway Performance Monitoring (HPM), were used to form the database for this study. A set of Structured Query Language (SQL) programs was developed to relate the subsystems, and to retrieve and compile data in a compatible format for data analysis. SAS 9.1.3 was then used to manage the data for statistical analysis.

In the database containing shoulder width data (SHD), shoulders are classified by pavement material into four types – curb, gravel, asphalt and concrete. For this study, only paved shoulders with either asphalt (bituminous concrete) or concrete (Portland cement concrete) pavement were used. In some segments, two or more types of shoulder pavement were found. Thus, a shoulder width in this study is a summation of widths of the contiguous hard shoulders (asphalt or concrete shoulder). For example, the shoulder width for a highway with 2 feet of asphalt shoulder abutting 4 feet of gravel shoulder is 2 feet in this study.

There were over 8,000 centerline miles of primary highways under VDOT's administration as of September, 2009. From this total, 320 miles of controlled access highways were identified for which data are available and bicycle permission/prohibition is known. Figure 8 depicts a data preparation process to form the final database for crash analysis. Reductions in the total centerline mileage are presented as an individual database is being merged.

Over 8,000 centerline miles of primary highways were identified in RDI database. After adding traffic volume data from HPM database, shoulder width data from SHD database, and traffic crash data from ACC database to each identified segment of the primary highways, the combined database reduced to about 6,600 miles. When selecting segments with partial or full control of access, the database further reduced to 404 miles. At last, prohibition data from our Bicycle Permission/Prohibition (BPP) database were added to the database resulting in 320 miles comprising 960 segments. Among the final 320 miles, 133 miles have bicycle prohibitions in place and 187 miles do not.

Only segments with valid information for all variables were included in the data analysis, including traffic crash frequencies (e.g., total crash, run-off-right crash, and bicycle-vehicle crash), segment length, the number of intersections in a segment, shoulder width, speed limit, and AADT. A total of 137 segments out of the 960 segments were removed due to incomplete data resulting in 823 segments over 268 miles available for data analysis. The final study database with 268 miles breaks down to 119 miles with bicycle prohibitions in place and 149 miles without prohibitions. Figure D-1 depicts the above described process of data preparation.



Note: RDI=Roadway Inventory, CA=Controlled Access, HPM=Highway Performance Management, SHD=Shoulder Width, ACC=Accident, BPP=Bicycle Permission/Prohibition

Figure D-1. Preparation of data from primary highways in Virginia.

APPENDIX E.
HIGHWAY AND CRASH CHARACTERSITICS BY PROHBITION STATUS

Tables E-1 through E-3 show statistics of Tables 3 through 5 by prohibition status, respectively.

Table E-1. Basic Statistics of Segment Characteristics by Prohibition Status

Variable	Prohibited			Permitted		
	Num. of obs.	Mean	Std. dev.	Num. of obs.	Mean	Std. dev.
AADT[1] (1,000 vehicles per day)	258	23.07	14.14	565	30.53	20.90
Length[2] (mile)		0.463	0.675		0.263	0.447
Curb and gutter[2,4] (1 if present; 0 if not)		0.0039	0.062		0.186	0.389
Number of intersections[2]		0.295	0.590		0.804	0.794
Number of lanes[2]		4.155	0.506		4.365	0.950
Speed limit[2] (miles per hour)		60.23	6.523		50.99	7.769
Shoulder width[3] (ft)		7.222	3.989		4.065	3.910

[1]2008 HPM database
[2]2008 RDI database
[3]Weighted average of right and left shoulder widths (only hard shoulders with asphalt or concrete pavement)

Table E-2 Number of Segments by Number of Lanes, Speed Limit, and Access Control Type and by Prohibition Status

Status	Variables	Num. of lanes						Speed limit							Access control	
		2	3	4	5	6	7	35	40	45	50	55	60	65	Partial	Full
Prohibited	Num. of segments	0	1	231	11	15	0	2	0	18	0	75	12	151	12	246
	Percentage (%)	0	0	90	4	6	0	1	0	7	0	29	5	59	5	95
Permitted	Num. of segments	18	6	414	14	105	8	45	13	178	6	216	86	21	310	255
	Percentage (%)	3	1	73	3	19	1	8	2	32	1	38	15	4	39	61

Table E-3. 3-Year Crash Frequency per Segment on Controlled Access Primary Highways by Prohibition Status (2005-2007)

Status	Prohibited			Permitted		
Crash type	Num. of obs. [1]	Mean	Std. dev.	Num. of obs. [1]	Mean	Std. dev.
All crash	258	5.182	6.664	565	7.770	11.50
Run-off-right crash		0.907	1.717		0.480	1.120
Single-vehicle crash		2.837	4.077		1.864	2.928
Off-travel-lane crash		2.248	3.568		1.487	2.346
Nighttime crash		1.857	2.659		2.150	3.262
Bicycle-vehicle crash		0.008	0.088		0.002	0.042

[1]Number of observations = number of segments

APPENDIX F.
CRASH PREDICTION MODELS FOR OTHER CRASH TYPES

In addition to the run-off-right crash type, the types of all crash, single-vehicle crash, and off-travel-lane crashes were analyzed and their crash prediction models using negative binomial regression mode specification were developed. The estimated final models are shown below.

$$Total\ Crashes\ in\ 3\ Years =$$
$$(Segment\ Length) \times \exp\begin{pmatrix} 4.740 + 0.263(Urban) - 0.052(Speed\ Limit) \\ + 0.144(Number\ of\ Intersections) + 0.122(AADT/1{,}000) \\ - 0.00207(AADT/1{,}000)^2 + 0.0000123(AADT/1{,}000)^3 \\ - 0.0256(Shoulder\ Width) \end{pmatrix} \quad \text{Eq. (F-1)}$$

$$Off\ Travel\ Lane\ Crashes\ in\ 3\ Years =$$
$$(Segment\ Length) \times \exp\begin{pmatrix} 1.943 - 0.180(Number\ of\ Lanes) + 0.0268(AADT/1{,}000) \\ + 0.0803(Shoulder\ Width) \\ + 0.276(Shoulder\ Width)(Shoulder\ Width < 5) \\ - 0.00643(Shoulder\ Width)^2 \\ - 0.0702(Shoulder\ Width)^2(Shoulder\ Width < 5) \end{pmatrix} \quad \text{Eq. (F-2)}$$

$$Single\ Vehicle\ Crashes\ in\ 3\ Years =$$
$$(Segment\ Length) \times \exp\begin{pmatrix} 1.335 + 0.0358(AADT/1{,}000) - 0.000242(AADT/1{,}000)^2 \\ + 0.0941(Shoulder\ Width) \\ + 0.347(Shoulder\ Width)(Shoulder\ Width < 5) \\ - 0.00718(Shoulder\ Width)^2 \\ - 0.0853(Shoulder\ Width)^2(Shoulder\ Width < 5) \end{pmatrix} \quad \text{Eq. (F-3)}$$

APPENDIX G.
A GUIDE FOR BICYCLE USE OF RIGHT SHOULDERS ON CONTROLLED ACCESS FACILITIES IN VIRGINIA

September 2014

This document shall serve as a guide not a warrant or requirement and is not for designing facilities for bicycle accommodation. This guide is applicable only for controlled access highways in Virginia without street parking. It provides guidance regarding when permitting bicycle use of right shoulders should be considered for either existing facilities where bicycles are currently prohibited or newly constructed facilities where appropriateness of bicycle use is being evaluated. It also provides guidance regarding when prohibiting bicycle use should be considered for existing facilities where bicycle use is currently permitted yet safety concerns arise due to the presence of bicycles. In general, facilities meeting the conditions described below should permit bicycles on right shoulders.

- The right shoulder shall meet the following conditions:
  - The entire shoulder surface is smooth paved with a texture equal to or better than the adjacent lane for motor vehicle travel.
  - Drainage grates and structures on the shoulders are acceptable for bicycle operations or adequate space is available for a bicyclist to safely go around these features.
  - The shoulder is not used as a travel lane by motor vehicles at any time (e.g., peak period use of the shoulder as a travel lane or a bus bypass shoulder).
- The right shoulder shall meet the following width criteria:

Minimum Widths of Paved Right Shoulder for Bicycle Use

Posted Speed Limit* (miles per hour)	Average Annual Daily Traffic Volume (AADT) (vehicles per day)	
	< 2,000	≥ 2,000
45	3 ft	4 ft
50	4.5 ft	
55	5.5 ft	
60	6.5 ft	
65	7 ft	

*An average operating speed based on actual speed data should be used instead if there is evidence that the operating speed is higher than the posted speed limit.

- When it is determined that a highway segment currently permitting access to bicyclists does not satisfy the conditions in the Guide, the existing permission shall not be removed until such time that an alternate facility or route is constructed and an engineering study of the segment is conducted.
- When it is determined that a highway segment currently permitting access to bicyclists does not satisfy the conditions in the Guide, the existing permission shall not be removed

when doing so would violate a person’s rights under the Americans with Disabilities Act (ADA).

- If a segment satisfies the conditions of the Guide but there is a known safety issue associated with bicycle use, efforts shall first be made to resolve the safety issue through engineering treatments such as signage or geometric changes before any prohibition of bicyclists is considered. Potential treatments are listed in the VDOT’s Traffic Engineering Design Manual.